PRACTICAL PHYSICS

A LABORATORY MANUAL FOR
COLLEGES AND TECHNICAL SCHOOLS

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BY

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VOLUME II

ELEMENTARY AND ADVANCED MEASUREMENTS
IN ELECTRICITY AND MAGNETISM

New York
THE MACMILLAN COMPANY
LONDON: MACMILLAN & CO., LTD.
1908

Set up and Electrotyped. Published January, 1908

PRESS OF
THE NEW ERA PRINTING COMPANY
LANCASTER, PA.

PREFACE.

The authors believe that physical laboratory work should accompany lecture and recitation work in physics from the beginning of the study of this science in the college or technical school, and they believe that a laboratory manual should set forth a series of definite exercises. A general discussion of how to measure a thing is, in their opinion, not a satisfactory basis for the laboratory work of a student. This laboratory manual has been prepared with these ideas in mind.

A group of students who are beginning a laboratory course on the basis of this manual should be required to study the introductory chapter to Volume I, and to solve the problems illustrating the calculation of probable error.

The system which has been used with great satisfaction by the authors in the assignment of laboratory exercises is described on page 2 of Volume I. The authors believe that one of the most important aspects of laboratory work in physics is that it gives to the student a series of more or less distinctly theoretical problems based upon experimental data obtained by themselves, and in accordance with this idea, the authors believe that a student should be required to work up his laboratory reports outside of the laboratory as specified on page 3 of Volume I.

This manual is issued in three small volumes. The first volume is devoted to Precise Measurements and to Experiments in Mechanics and Heat; the second volume is devoted to Elementary and Advanced Measurements in Electricity and Magnetism; and the third volume is devoted to Photometry and to Experiments in Light and Sound.

The authors wish to acknowledge their obligations to Dr. Howard L. Bronson, of McGill University, for suggestions concerning Experiment 107 on Radio-activity, and the authors'

thanks are due to Professor Wilbur M. Stein for the use of three cuts from his book on Photometric Measurements, and to Leeds & Northrup for the use of twelve cuts illustrating some of their electrical measuring instruments.

THE AUTHORS.

SOUTH BETHLEHEM, PA.,
December 22, 1907.

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GENERAL DIRECTIONS FOR THE USE OF ELECTRICAL APPARATUS.

Connections. — Most of the trouble which is encountered in the carrying out of electrical measurements arises from faulty connections. In some cases a faulty connection has no other effect than to make the apparatus inoperative; in other cases, a faulty connection may lead to serious damage to the apparatus.

Always make a diagram of the connections desired for any experiment, showing positions of battery, rheostat, galvanometer, switches, and every other device used, before a single connection is made and then follow this diagram in making the connections.

Wires leading from an instrument on a table should be clamped to the edge of the table so that the instrument may not be pulled off the table by the wires.

The source of current supply is to be connected after all other connections have been completed. Make sure that the connections are correct and that the instruments are safe. Clear away doubt by forethought, not by damaging an instrument. The usual causes of damage are specified under the following headings: Resistance boxes, rheostats, voltmeters, and ammeters.

When connections have been completed, a trial connection of the source of current is to be made and instantly broken to see if there are any indications of a short-circuit. These precautions are especially necessary when current is taken from a dynamo generator (that is from the electric supply mains in the laboratory) or from a storage battery.

In all cases, make connections to the source of current supply through a double-pole switch and a double-throw fusible cut-out, except where only a few cells of battery are used to supply current.

When a network of circuits is to be dismantled at the end of an

experiment, the source of current supply is first of all to be disconnected. Always avoid the making or the changing of connections with live wires. Disconnect the source of current supply when connections are to be changed in any way.

In making connections, scrape the ends of the wires clean, and clamp them firmly into the binding posts. To connect two wires together, scrape the ends clean and make what is called a telegraph splice. If the connection is to be permanent, it should be soldered.

Soldering. — The soldering iron or copper is useful only in soldering very small wire or in soldering thin sheet metal. Large wires and thick sheets of metal cannot be sufficiently heated by the soldering iron, and they are usually soldered by direct application of the flame of the blow-pipe or torch. It is usually not desirable to use zinc chloride (soldering "acid") in soldering, on account of the subsequent tendency to corrosion. To solder with rosin, proceed as follows: Clean the wires or sheet by scraping, fix the parts to be soldered in position by twisting or otherwise, cover thoroughly with powdered rosin or rosin solution (in alcohol), heat slowly and rub wire-solder against the joint so that the solder may strike in before the rosin is burned off. The most important thing in soldering with rosin is to avoid the exposure of the hot metal surface to the air by the burning off of the rosin before the solder is applied.

The soldering copper should be thoroughly tinned at the tip, it should be wiped clean before being applied to the joint to be soldered, and a plentiful supply of solder should be allowed to flow between the copper and the metal to be soldered so as to facilitate the conduction of heat into the metal from the copper. The joint should be clean and covered with rosin before the application of the hot copper. A soldering copper should not be allowed to get red hot.

Switches and fuses. — Always open or close a switch suddenly so as to avoid the melting of the contact points of the switch.

To replace a fuse-link in a cut-out, disconnect the source of

current supply and then proceed to remove the old link and put in a new one. Serious burns frequently result from careless use of the screw driver and fuse-link on a cut-out block which is not disconnected from the supply mains.

Keys and switches. — The ordinary contact key can be used only where a small current is to flow through it, and where variations of contact resistance are not objectionable. For moderately large currents, the so-called knife switch should be employed, except where the resistance of the switch must be very small and constant in value, in which case the circuit should be opened and closed by means of a copper rod connecting two mercury cups.

The double-contact key. — In the use of the Wheatstone's bridge the battery circuit should always be closed first and the galvanometer circuit afterwards. A single device called the double contact key is sometimes used for this purpose. It consists of two small keys one above the other, but insulated from each other. Pressure on the key closes the upper key first and the lower key afterwards. The upper key is to be placed in the battery circuit and the lower key in the galvanometer circuit.

Reversing switches. — It is frequently necessary to repeatedly reverse the current through a portion of an electric circuit. For this purpose a reversing switch is always used. A very simple form of reversing switch is shown in Fig. 76. It consists of four binding posts connecting to four mercury cups 1, 2, 3 and 4, as shown, and two copper rods are arranged so that they can be placed in the position shown by the heavy black lines in Fig. 76, or in the position shown in the double dotted lines. The portion of the circuit AB in which the current is to be reversed is connected to one pair of diagonally opposite binding posts, and the battery is connected to the other pair of binding posts as indicated in the figure.

Another type of reversing switch, which is frequently used in the laboratory, consists of a block of wood at the ends of which are two pairs of binding posts which are connected to six mercury cups 1, 2, 3, 4, 5 and 6, as indicated in Fig. 77. A rocker is arranged so as to connect the mercury cups as shown by the

heavy black lines or as shown by the double dotted lines. The portion of the circuit *AB* in which the current is to be reversed

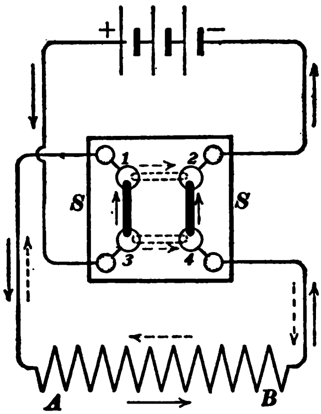

Fig. 76.

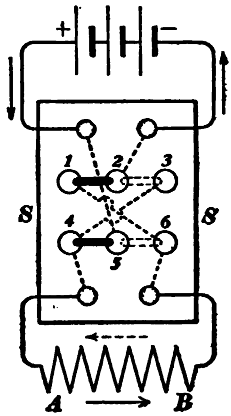

Fig. 77.

is connected to the binding posts at one end of the block, and the battery is connected to the binding posts at the other end of the block. This type of reversing switch is very apt to form a short-circuit, and it should never be used for reversing the connections of a circuit which takes current from a dynamo or storage battery.

The ordinary double-pole double-throw knife switch is frequently used as a reversing switch, in which case it is connected as shown in Fig. 78.

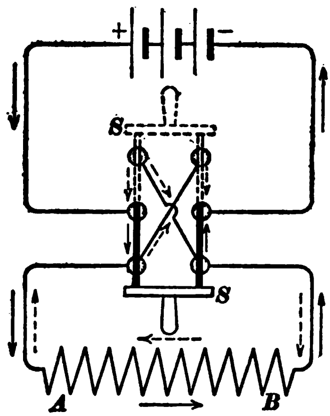

Fig. 78.

Resistance boxes. — The coils of the ordinary resistance box are made of comparatively fine wire and they are not capable of carrying any considerable amount of current. Especial care must therefore be exercised in the use of resistance boxes in circuits supplied from storage batteries or dynamos.

The terminals of the coils in a resistance box are connected to heavy brass blocks on the top of the box, and these blocks are arranged to be connected together by conical brass plugs. Each of these plugs short-circuits a resistance, the value of which is marked at one side of the socket into which the plug fits, and when the plug is removed the specified resistance is included in the circuit.

These metal plugs should be put in place with a slight turning motion under *moderate* pressure. To clean the plugs, wipe them with a bit of cloth very slightly wetted with petroleum.

A resistance box is generally used in a manner analogous to the use of a set of weights in weighing a body. In the use of a set of weights, the weights are always tried in order of magnitude; if the first weight is too large, it is set aside and the next smaller weight is tried; if this is too small, it is left on the balance pan and the next smaller weight is added to it; if this is too large, it is set aside and the next smaller weight is tried; if this is too small, it is left on the balance pan and the next one is tried; and so on. An exactly similar procedure should be followed in adjusting a resistance box so as to balance a Wheatstone's bridge.

A resistance box, or potentiometer, having a hard rubber top should be protected from the light as much as possible, inasmuch as strong light causes the rubber to oxidize. It is for this reason, mainly, that such instruments are provided with covers, and these covers should always be in place when the instrument is not in use.

Rheostats. — A rheostat is a conveniently arranged portion of an electrical circuit having an adjustable resistance.

The *water rheostat* consists of two metal electrodes, usually iron, in a vessel of water. The resistance of such a rheostat may be altered by varying the amount of salt in solution, or by moving one or both electrodes. The water rheostat can scarcely be damaged by excess of current and it is especially useful for very heavy currents.

A convenient form of rheostat is the *lamp bank* which consists

of a number of glow lamps connected in parallel. The number of lamps required in a lamp bank for use as a rheostat for any given case may be estimated on the basis that 110-volt 16-candle-power carbon filament lamp has a resistance (hot) of about 220 ohms. In using a lamp bank the lamps should not be subjected to more than their rated voltage of 55 volts, 110 volts, or 220 volts as the case may be. A lamp bank is not suitable for a low resistance rheostat. The resistance of a lamp bank changes by steps when lamps are connected or disconnected, and therefore a lamp bank is not suitable where fine adjustments are to be made.

Rheostats made of strips of tinned sheet iron have a large current carrying capacity and are very satisfactory. Their chief defect is that they are subject to quick changes of temperature especially in a room where there is the least draught of air, and these changes of temperature cause changes of resistance and produce fluctuations of current.

The *carbon plate rheostat*, the essential features of which are shown by *R*, Fig. 109, consists of a stack of carbon plates, the resistance of which is varied by means of a clamping screw. The current is led into and out of this rheostat through two metal plates between which the plates of carbon are placed.

A type of rheostat which is frequently used is shown in Fig. 79. It consists of a bare german silver wire *ww* stretched on a

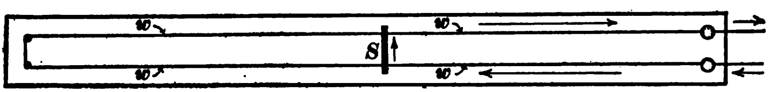

Fig. 79.

board, and a weighted metal slider *S* which can be moved back and forth at will, thus short-circuiting any desired portion of the wire and leaving the remainder of the wire in circuit.

Voltaic cells. — Many electrical measurements require but little current, and the current need not be steady in value. Thus, a Wheatstone's bridge can be operated with one or two dry cells if a moderately sensitive galvanometer is available. The ordinary dry cell is also a satisfactory source of current for many experi-

ments with the ballistic galvanometer. When used for this purpose, the electromotive force of the cell should be constant, and this requires that the cell be never used to deliver any considerable amount of current.

When it is desired to maintain a very steady current in a circuit, a storage cell is perhaps the best source of supply. In the standardization of an ammeter, the storage cell is by far the best source of supply. If a storage cell is not available, several gravity (Daniell) cells may be used.

To set up a gravity cell the plate of copper with a gutta-percha covered connection wire is placed in the bottom of the glass jar, and nearly covered with crystals of copper sulphate. The zinc electrode is then placed in the top of the jar, and the jar is filled with very dilute sulphuric acid (1 part of acid to 20 or 30 parts of water by volume). The gravity cell should not be stirred and therefore the gutta-percha covered wire should lead to a binding post fixed to a base board, and the cell should be carried about with care. The zinc should be occasionally removed and cleaned. The electromotive force of the ordinary gravity cell varies from 1.08 to 1.02 volt.

In the *chromic-acid cell*, which is commonly known as the Grenet cell, the zinc should be thoroughly amalgamated. This is most easily done by dipping the zinc into dilute sulphuric acid and rubbing a little mercury over it. The solution used in the chromic-acid cell is made up by dissolving 92 grams of pulverized potassium bichromate in dilute sulphuric acid (94 cubic centimeters of H_2SO_4 and 900 cubic centimeters of water). This solution should be diluted with water if the zinc is to stand in the solution for a long time.

To obtain a small known electromotive force, a current i measured by an ammeter, may be allowed to flow through a bare german silver wire of which the resistance r per unit length is known. Then the electromotive force e between any two points on the wire is given by the equation

$$e = lri$$

where l is the distance between the points. This method of obtaining a small known electromotive force is especially useful when one wishes to produce a known current through a galvanometer circuit of known resistance.

International standards. — All electrical measurements for commercial and technical purposes are based upon the international standard units.

The international standard ohm is the resistance at the temperature of melting ice of a column of pure mercury 106.3 centimeters long, of uniform cross-sectional area and weighing 14.4521 grams. For actual use copies of this standard ohm and multiples of it are made of wire.

Standard resistances. — Single resistance standards are usually arranged as shown in Fig. 80. The wire which constitutes the

Fig. 80.

resistance is wound on a thin metal cylinder which is covered with insulating paper, and the terminals are connected to heavy copper rods as shown. The resistance is submerged in an oil-bath and a thermometer is introduced into the interior through a hole in the top of the containing case.

It is frequently desirable to measure the electromotive force between the terminals of a standard resistance when a fairly large current flows through it. In this case the current terminals and electromotive force terminals of the resistance standard are separate, as shown in Fig. 81.

Fig. 81.

The international standard ampere is a current which when passing through a solution of pure silver nitrate in accordance with the following specifications will deposit 0.001118 gm. of silver per sec.

For currents as large as one ampere the cathode on which the silver is deposited is in the form of a platinum bowl not less than 10 centimeters in diameter, and from 4 to 5 centimeters in depth. This bowl serves at the same time as containing vessel for the solution.

The anode is a plate of pure silver about 30 square centimeters in area and two or three millimeters in thickness. This plate is supported by platinum wires in a horizontal position near the top of the solution in the platinum bowl. To prevent detached particles from falling from the anode to the bottom of the bowl the anode is wrapped with clean filter paper.

The electrolyte consists of a neutral solution of pure silver nitrate, containing about 15 parts by weight of silver nitrate to 85 parts by weight of water.

The circuit should contain not less than 10 ohms of metallic resistance so that the variations in the resistance of the cell may not produce large fluctuations of current.

The platinum bowl is washed with nitric acid, then with distilled water, dried at about 160° C., left to cool in a desiccator, and weighed.

It is then placed upon a clean sheet of copper to which the circuit is connected, and nearly filled with the electrolyte.

The anode is then suspended in position, all connections are made except a key, and when this is closed the clock reading is observed.

The ammeter which is being standardized should be read at equal intervals of time during the test, which should continue for at least half an hour, and the clock reading is again taken when the key is opened.

The solution is now removed from the bowl, the deposit is thoroughly washed with distilled water, the bowl is dried at about 160° C., cooled in a desiccator, and weighed.

The current used in this work must be from a battery, especially when an electrodynamometer is standardized.

The international standard volt is an electromotive force which will produce an international standard ampere of current through a resistance of one international standard ohm. The international standard volt is represented with sufficient accuracy for all ordinary purposes by 1,000/1,434 of the electromotive force of the standard Clark cell at a temperature of 15° C.

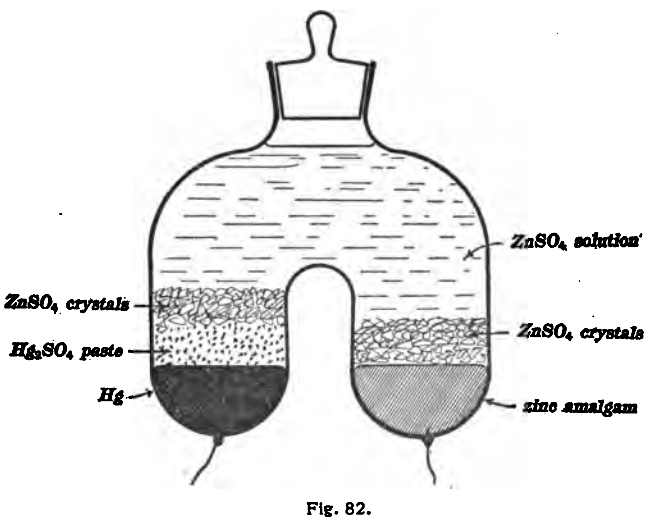

Fig. 82.

The Clark cell. The usual arrangement of the standard Clark cell is shown in Fig. 82. This cell is extensively used as a

standard of electromotive force, and the value of its electromotive force in volts at temperature t° C. is given by the equation:

$$E = 1.4292 - 0.00123(t - 18) - 0.000007(t - 18)^2.$$

(*b*) *The Weston cell* is similar in every respect to the Clark cell except that cadmium amalgam and cadmium sulphate are used instead of zinc amalgam and zinc sulphate. The electromotive force in volts of the cadmium cell (with concentrated solution) at t° C. is given by the equation:

$$E = 1.0187 - 0.000035(t - 18) - 0.00000065(t - 18)^2 ,$$

Preparation of materials for the Clark cell. — 1. The mercury should be chemically purified and then distilled *in vacuo*.

2. Pure re-distilled zinc should be used. This is sold by chemical dealers in small rods. To prepare the zinc amalgam take one part by weight of zinc and nine parts by weight of mercury. Place in a porcelain dish over a water-bath and stir until the zinc dissolves.

3. If the mercurous sulphate, purchased as pure, is not colored yellow with a basic salt, mix it with a small quantity of mercury and agitate it with cold distilled water, two parts by weight of water to one part of the salt. Drain off the water and repeat the process until a very faint yellow tint appears. After the last washing drain off as much water as possible, but do not dry by heating.

4. The zinc sulphate solution is prepared by mixing in a flask one part by weight of distilled water, two parts by weight of pure zine sulphate crystals, and about one fiftieth part by weight of pure zinc oxide to neutralize any free acid. Heat gently, not to exceed 30° C. for about two hours with frequent agitation, and set the solution away over night. Then add mercurous sulphate, as prescribed in 3, in the proportion of about 12 per cent. of the zinc sulphate crystals used. Warm the mixture gently, agitate, and filter while warm into a glass-stoppered bottle. Crystals of zinc sulphate should form in this bottle upon cooling.

5. The mercurous sulphate and zinc sulphate paste. To three parts by weight of the washed and dried mercurous sulphate add one part of pure mercury and grind it in a clean dish with a mixture of zinc sulphate crystals and concentrated solution of zinc sulphate, making a stiff paste showing crystals of zinc sulphate and globules of mercury throughout. Keep this paste in a covered dish to prevent drying.

*Setting up the Clark Cell.** — Place pure mercury in one limb of the glass containing cell, and hot fluid zinc amalgam in the other limb, covering completely the platinum wires. On the mercury place a layer about one centimeter thick of the zinc and mercurous sulphate paste. Cover both the paste and the zinc amalgam with neutral zinc sulphate crystals one centimeter thick, and fill the vessel nearly full of the zinc sulphate solution, so that only a small bubble will remain under the stopper.

* Directions for setting up standard cells, Clark and Weston, may be found on pages 118 to 128, Vol. VI., of the *Transactions of the American Electrochemical Society*.

Introduce the mercury first by means of a clean dropping tube. Place the porcelain dish of amalgam in a hot water-bath, also the glass cell. With a clean dropping tube of glass suck up a small portion of the amalgam and transfer it to the cell, and continue the process until the desired quantity is in the cell. The point of the dropping tube must be so fine that the amalgam will flow out only by squeezing the bulb. The cell is now removed from the hot water-bath and allowed to cool. The paste may be introduced through a wide tube reaching nearly to the mercury and having a funnel top. Push the paste through the tube with a clean glass rod. Use the same tube, cleaned, for introducing the zinc sulphate crystals and pour the zinc sulphate solution in through a small funnel. The greatest care must be taken not to mix the materials and not to soil the neck of the cell.

Brush the stopper around its upper part with a thick alcoholic solution of shellac and press it firmly in place.

Condensers. — A general view of a standard form of subdivided condenser is shown in Fig. 83, and the internal connections of

Fig. 83.

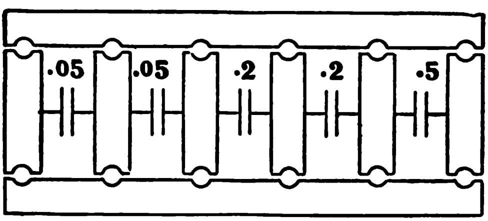

Fig. 84.

this subdivided condenser are shown in Fig. 84. The binding-post terminals are connected to the two long parallel metal bars, and the arrangement of the plugs which is necessary to connect any number of the subdivisions of the condenser in parallel may

be readily seen from the figure. When the parts of the condenser are connected in parallel the combined capacity is equal to the sum of the capacities of the parts. The arrangement shown in Fig. 84 also permits of the connection of the parts in series. When the parts are so connected, their combined capacity is equal to the reciprocal of the sum of the reciprocals of the individual capacities.

Ammeters. — An ammeter is to be connected in the circuit in which the current to be measured flows. Before connecting the source of supply of current be sure that an excessive current will not flow through the ammeter. If the actual conditions as they exist in the circuit are not sufficient to indicate approximately what the current will be, connect a suitable rheostat in circuit with the ammeter and cut this rheostat out cautiously after final connections of the source of supply of current have been made.

Ammeters are most frequently damaged by being thoughtlessly connected between supply mains with little or no resistance in series with them.

Use of millivoltmeters with interchangeable shunts as ammeters. — The current I flowing in a circuit may be determined by measuring, with a millivoltmeter, the voltage drop RI across a known resistance R connected in the main circuit. The resistance R is called a shunt in its relation to the millivoltmeter, and the shunt and millivoltmeter together constitute an ammeter.

Most laboratories are provided with a series of shunts any one of which may be used with any millivoltmeter. *Never connect the current leads and the millivoltmeter leads to the same set of terminals on the resistance R.*

Voltmeters. — A voltmeter is to be connected to the points between which the voltage is to be measured. Voltmeters are frequently made with several sets of terminals so that full deflection may be obtained, say, for 3 volts or for 150 volts. *Under no circumstances should the low voltage terminals of an instrument be connected to a high voltage source.*

A voltmeter may be marked as a 150-volt instrument with the

understanding that the instrument is to be used in series with a multiplying coil. Such an instrument would be ruined by connecting it directly to 110-volt mains without including the multiplying coil. Any voltmeter is damaged by a voltage greatly in excess of what the instrument is intended to measure. Therefore, when a low reading voltmeter (3-volt, 5-volt, or 15-volt) is used for taking readings in a net-work supplied from a high voltage source, make sure that the instrument is safe before connecting the net-work to the supply mains.

Galvanometers. — In many electrical measurements it is necessary to make a certain adjustment so that no current may flow in a given portion of the circuit or so that the electromotive force between two points may be equal to zero. Methods which involve this adjustment are called the *zero methods.* In carrying out a zero method, a sensitive galvanometer is placed in the given portion of the circuit, or connected between the two given points, and the adjustment is varied until the galvanometer shows no deflection.

The Thomson Galvanometer. — This galvanometer consists of an astatic pair of magnet needles suspended by a fine fiber, each magnet needle being at the center of a coil of wire as shown in Fig. 85. In this galvanometer the coils must be connected together so that the current may flow in opposite directions around the two coils as indicated by the arrows in Fig. 85. The result of this arrangement is that the two coils work together to deflect the suspended magnets, whereas the earth's magnetic field has a very weak directive action upon the suspended system. An auxiliary permanent magnet called a *governing magnet* is always so placed in the neighborhood of the galvanometer as to bring the suspended system to the desired zero position, and the distance of this magnet from the instrument is then altered until the desired degree of sensitiveness is obtained.

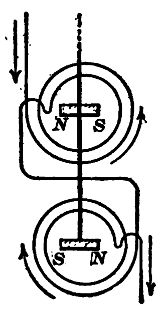

Fig. 85.

The Thomson galvanometer is extremely sensitive to magnetic disturbances. It cannot be used near moving machinery, especially near electromagnetic machinery such as a dynamo or a motor, and the observer must remove all steel articles, such as knives and keys, from his pockets.

The D'Arsonval galvanometer. — This galvanometer consists of an elongated coil of fine wire suspended between the poles of a horse-shoe magnet. Current is led into the coil through the fine suspending wire, and out of the coil through a fine helical spring. The D'Arsonval galvanometer is not at all sensitive to magnetic disturbances, but it should be mounted upon a solid pier or shelf so as to be free from mechanical disturbances.

Directions for using the sensitive galvanometer. — During the preliminary adjustments in the performance of a zero method for making an electrical measurement, *the galvanometer must be protected by means of a shunt* through which the major part of the current may flow. When the adjustment has been carried as far as possible with the shunted galvanometer, the shunt may be opened and the adjustment completed.

The sensitive galvanometer is nearly always used for showing the mere existence of a current, and for indicating its direction. A great deal of time will be saved by manipulating the galvanometer as follows:

(*a*) A quick tap on the galvanometer key is generally sufficient to indicate the direction of the current; whereas to close the key for a longer interval of time, sets the galvanometer swinging, and a great deal of time is lost in waiting for the galvanometer to come to rest.

(*b*) After the galvanometer has given an indication of the direction of the current, and before any changes are made in the adjustment of the apparatus, bring the galvanometer to rest by tapping the galvanometer key at the moment when the galvanometer is moving in the direction opposite to that in which it will be deflected. When the D'Arsonval galvanometer is used as a

ballistic galvanometer, this method of bringing the galvanometer to rest is not applicable.

The ballistic galvanometer. — The D'Arsonval type of galvanometer is now almost universally used in electrical measurements. When such a galvanometer is to be used as a ballistic galvanometer the period of oscillation of the suspended coil should be 20 seconds or more. When the circuit of such a galvanometer is closed, the oscillations of the suspended coil are greatly damped by the induced current produced by the motion, and the less the resistance of the galvanometer circuit (including any coil which may be connected to the galvanometer terminals), the greater the damping. When the circuit of a galvanometer is open, however, the suspended coil continues to oscillate for a long time when once set in motion; and when the galvanometer is connected to the terminals of a condenser, it behaves as if it were on open circuit. Therefore, two distinct cases arise in the use of the D'Arsonval type of ballistic galvanometer, namely: (*a*) when the galvanometer is used to measure the discharge of a condenser, and (*b*) when the galvanometer is used to measure a momentary induced current. In the first case, the galvanometer is practically on open circuit, and in the second case, the galvanometer circuit is closed through the coil in which the induced current is produced.

(*a*) When the ballistic galvanometer is used to measure the discharge q from a condenser, the charged condenser is connected to the galvanometer terminals, and the galvanometer throw d is observed. Then

$$q = kd \tag{i}$$

in which k is the constant which is to be determined by observing the throw produced by a known discharge. For example, a condenser of known capacity C may be charged by a known electromotive force E and discharged through the galvanometer, giving $q = EC = kd$, from which k may be calculated.

(*b*) The following example will serve to elucidate the second

use of the ballistic galvanometer. In this case the galvanometer really measures what is called the *impulse value* of the momentary induced electromotive force. A coil containing Z turns of wire is connected to a ballistic galvanometer and slipped over a steel rod through which there is a definite amount of magnetic flux Φ. The coil is then very quickly removed from the rod, and the galvanometer throw d is observed. This throw is proportional to the product $Z\Phi$, so that we may write

$$Z\Phi = k'd \tag{ii}$$

in which k' is a constant *for a given value of the resistance of the galvanometer circuit*, and it is to be determined by observing the throw produced by a known value of $Z\Phi$ If the resistance of the galvanometer circuit is changed the value of k' is altered.

This example may be made more intelligible by considering more in detail the significance of the product $Z\Phi$. Let t be the short interval of time which elapses during the removal of the coil. Then the flux through the coil changes from Φ to zero in time t, the average rate of change of the flux is Φ/t, and the average value of the electromotive force which is induced in the coil during the time t is $Z\Phi/t$ abvolts. The effect of

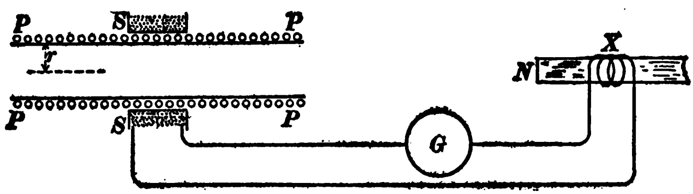

Fig. 86.

this momentary electromotive force on the ballistic galvanometer is proportional to the product of the average value of the electromotive force and the time, *this product is called the* **impulse value** *of the momentary electromotive force*, and it is evidently equal to $Z\Phi$.

The galvanometer circuit is connected so as to include the small exploring coil X, Fig. 86, which is to be used with the

galvanometer after it is standardized, and also to include a coil of fine wire SS which is wound around the middle of a long cylindrical coil PP. A known current i sent through the coil PP produces an amount of flux through the coil SS which is equal to

$$\Phi = \frac{4\pi^2 r^2 Z' i}{l}$$

in which r is the radius of the coil PP in centimeters, l is the length of the coil PP in centimeters, and Z' is the number of turns of wire in PP; the current i is supposed to be expressed in abamperes. Therefore, when the current i is suddenly reduced to zero, the impulse value, $Z\Phi$, of the electromotive force induced in the coil SS is

$$Z\Phi = \frac{4\pi^2 r^2 Z Z' i}{l} \; (= k'd)$$

where Z is the number of turns of wire in SS; and if the throw of the ballistic galvanometer is observed when the current i in the coil PP is suddenly reduced to zero the constant k' of the galvanometer can be calculated.

Device for controlling the ballistic galvanometer.—The motion of the ballistic galvanometer cannot be controlled in the manner described on page 16. A convenient form of controller for the ballistic galvanometer is shown in Fig. 87. Three keys, k, l, r, and a switch S are mounted on a small block and connected to two pairs of binding posts B and G, as shown by the dotted lines. A dry cell C is connected to the binding posts B, and when the key k is closed the cell produces current through a

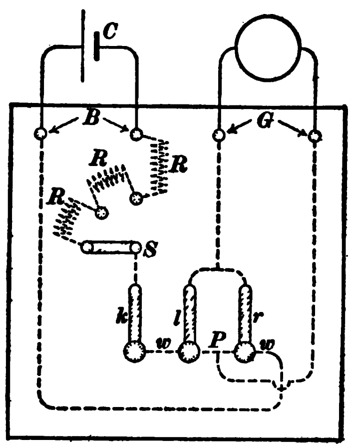

Fig. 87.

considerable resistance R and through the wire ww. The galvanometer is connected to the two posts G, one of which is permanently connected to the middle point P on the wire ww, and the other is connected to the two keys l and r. When the key k is closed, the closing of the key l produces a small deflection of the galvanometer in one direction, and closing the key r produces a small deflection of the galvanometer in the opposite direction. By properly manipulating the three keys, k, l, r, the movements of the galvanometer may be easily controlled. The connections of the galvanometer to the two posts G are made independently of the connections of the galvanometer to the measuring apparatus.

EXPERIMENT 62.

Resistance of Gravity Cell by the Tangent Galvanometer.

The object of this experiment is to determine the resistance of a gravity cell by means of the tangent galvanometer. This method can be used only in the case of cells of which the electromotive force does not fall off appreciably when they deliver current.

Theory. — A gravity cell of which the resistance is b is connected to a tangent galvanometer and the galvanometer deflection ϕ' is observed. Then, since the current is equal to the electromotive force of the cell divided by the resistance of the circuit and also proportional to the tangent of the angle of deflection ϕ', we have:

$$\frac{E}{b+G} = k \tan \phi' \tag{1}$$

in which G is the resistance of the galvanometer and connecting wires.

A known additional resistance r is connected in the circuit and the reduced deflection ϕ'' is observed, giving

$$\frac{E}{b+G+r} = k \tan \phi'' \tag{2}$$

From equations (1) and (2) determine the resistance of cell and galvanometer, $b + G$.

A second gravity cell whose resistance is b', is substituted for the cell b, and the resistance $b' + G$ is determined as before.

The two cells are then placed in series in the circuit, and the resistance $b + b' + G$ is determined in the same way.

From the values thus obtained, the values of b, b' and G may be determined.

Work to be done. — Connect the galvanometer, through two fairly long, twisted leads, to a reversing switch; and connect the gravity cell and a resistance box in series beyond the switch. The object of the long twisted leads is to avoid the deflection of the galvanometer needle by portions of the electric circuit other than the galvanometer coil. Magnetic disturbances must always be avoided; place all knives and keys at a distance from the galvanometer.

Bring the coil into a vertical position by adjusting the leveling screws of the galvanometer. This adjustment may be made sufficiently accurate by the eye.

Bring the plane of the galvanometer coil into the magnetic meridian by turning the instrument until the magnetic needle stands approximately parallel to the plane of the coils.

Errors due to inaccuracy of adjustment of the plane of the coil into the magnetic meridian may be eliminated by reading the deflection for a given current twice, first with the current flowing through the galvanometer in one direction and second with the current reversed. Errors due to inaccurate centering of the pivot with respect to the divided circle (eccentricity errors) may be eliminated by reading both ends of the pointer. The way in which the observed deflection ϕ is to be derived from the readings can be easily seen from the way in which the circle divisions are numbered.

A tangent galvanometer is usually provided with several distinct coils (that is, electrically distinct, although they are all wound on one spool), and each coil has its own terminals.

(*a*) Select that galvanometer coil which will give nearest 60° deflection when a single gravity cell is connected, resistance in the box being zero, and take the readings which determine the value of ϕ'.

(*b*) Put sufficient box resistance r in circuit to reduce the deflection to about 30° and take the readings which determine ϕ''.

Put the second cell in place of the first, and take observations as in (*a*) and (*b*). Put both cells in circuit, and take observations in like manner.

In doing this work great care must be taken to keep the resistance of connections constant. See that all contacts are made tight in binding posts, and that the plugs of the resistance box are clean and fit tightly. Otherwise large errors will result.

Computations and results. — From the data thus obtained, compute the values of $b + G$, $b' + G$, and $b + b' + G$. Then compute the values of b, b', and G. The value obtained for G will, of course, include the resistance of connections.

EXPERIMENT 63.

THE SLIDE-WIRE POTENTIOMETER.

The object of this experiment is to compare the electromotive forces of several voltaic cells by means of the slide-wire potentiometer.

Theory. — A slide wire is a bare wire stretched on a board, and provided with one or two sliding contacts. If a constant current is made to flow through the wire, then the electromotive force between any two points on the wire is equal to ri, where i is the current in the wire, and r is the resistance of the intervening portion of the wire; but r is proportional to the length of the portion of the wire under consideration, so that an electromotive force in any portion of the wire is proportional to the length of the portion. A stretched wire carrying a constant current may therefore be used as a measuring stick, as it were, for comparing the electromotive forces of voltaic cells, if a method can be devised for locating pairs of points on the wire between

which the electromotive forces are equal to the electromotive forces of the respective cells.

In order to locate a pair of points so that the electromotive forces between them will be equal to the electromotive force of a

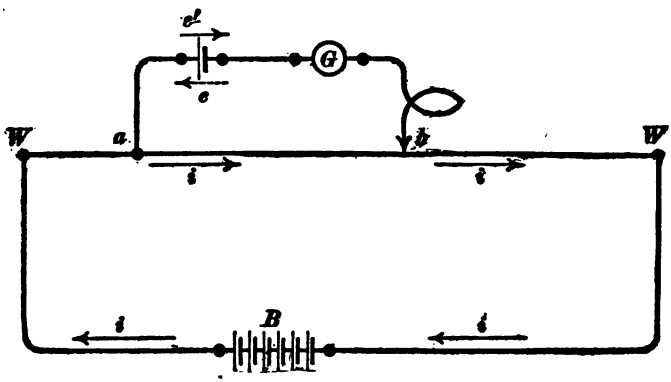

Fig. 88.

given voltaic cell, the given voltaic cell *e*, Fig. 88, is connected in series with a sensitive galvanometer *G*, one end of this circuit is connected to the slide wire *WW* at *a*, and the sliding contact *b* is moved until the galvanometer gives no deflection. The electromotive force between the points *a* and *b* is then equal to the electromotive force of the cell *e*. In order that the two points *a* and *b* may be located in this way, the battery *B* which produces the constant current *i* in the slide wire must have a considerably larger electromotive force than the voltaic cell *e*, and the cell *e* must be connected so as to tend to produce current in the direction of the dotted arrow *e*, the direction of the current produced by the battery *B* being indicated by the full-line arrows in Fig. 88.

Work to be done. — (*a*) Connect the slide wire to the constant source of current, preferably a storage battery. Connect the standard cell *e* and the galvanometer as shown in Fig. 88 and determine the length *ab* for which the galvanometer gives no deflection.

(*b*) Connect the cell of unknown electromotive force in place of the standard cell, and again determine the length ab for which the galvanometer gives no deflection.

(*c*) Replace the standard cell and re-determine the length ab for which the galvanometer gives no deflection.

(*d*) Repeat (*a*), (*b*) and (*c*) for each of the cells of which the electromotive forces are to be determined.

In determining the length ab, the position of b for which the galvanometer gives no deflection should be approached alternately from the left and from the right. In this way the errors due to lack of sensitiveness of the galvanometer are likely to be in part positive and in part negative, so that they tend to drop out in the final average if the point b is located three or four times in each case.

If it is impossible to locate the point b so as to give no deflection of the galvanometer, either the cell e, Fig. 88, is connected in the wrong direction, or the current i in the slide wire is too small. A preliminary test made by momentarily touching the galvanometer key when the points a and b are close together, and again when they are at opposite ends of the slide wire will show whether a balance point can be found on the wire, and this preliminary test will also indicate which direction of deflection means "ab too short."

During the preliminary adjustment of the point b, the galvanometer must be shunted, and the final adjustment should be made with the galvanometer shunt opened, so as to enable the full sensitiveness of the galvanometer to be used.

A standard cell should never be called upon to give any appreciable current. — Therefore, a large resistance should be connected in series with the standard cell in the preliminary adjustments of the point b, which resistance may be short-circuited when the final adjustment of the point b is made.

Computations and results. — From the known electromotive force of the standard cell (see page 12) and the observed lengths on the slide wire compute the electromotive force of each of the cells tested.

EXPERIMENT 64.

The Slide-wire Bridge.

The object of this experiment is to measure a resistance by means of the slide-wire bridge.

Theory. — The slide-wire bridge is a stretched wire with a sliding contact which divides the wire into two parts which are used as the ratio arms of a Wheatstone's bridge. The diagram of connections is shown in Fig. 89, in which *ab* is the slide wire, α is a known resistance, and β is the unknown resistance

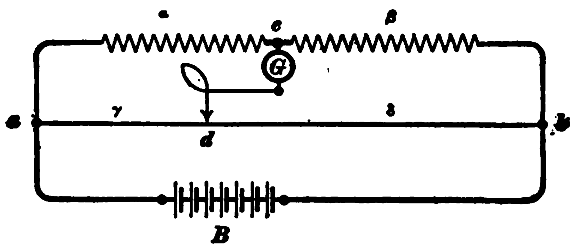

Fig. 89.

which is to be measured. The sliding contact *d* is adjusted until the galvanometer gives no deflection. Then

$$\frac{\alpha}{\beta}=\frac{\gamma}{\delta} \tag{i}$$

In using a Wheatstone's bridge the battery circuit and the galvanometer circuit should stand open; and when it is desired to test the balance to see if the ratio γ/δ is correct, the battery circuit is to be closed first and the galvanometer circuit afterwards. This avoids the momentary throw of the galvanometer which may be produced by inductance effects even though the ratio γ/δ is correct. The connection of battery and galvanometer in succession is most conveniently accomplished by means of a "double-contact" key which consists of two electrically separate keys, one above the other.

Errors in the use of the slide-wire bridge. — The error of setting

of the slider produces the least error in the ratio γ/δ when the balance position of the slider is near the middle of the slide wire. Hence the importance of choosing a known resistance approximately equal to the unknown resistance to be measured.

Non-uniformity of the slide-wire introduces errors, the complete elimination of which depends upon a careful calibration of the wire. The interchange of known and unknown resistances eliminates the greater portion of the errors due to non-uniformity of the slide wire if the balance position of the slider is near the middle of the wire.

Errors due to thermo-electromotive forces at the points of junction of different kinds of metal may be eliminated by reversal of battery connections.

Work to be done. — Connect a dry cell through a reversing switch and through the upper contact of the double-contact key to the ends of the slide-wire, and connect a resistance box α, and unknown resistance β, as shown in Fig. 89. Connect the galvanometer through the lower contact of the double-contact key to the slider and to the common junction of known and unknown resistances. Be sure that all connections are securely made.

With the galvanometer well shunted and any convenient value of known resistance in the resistance box α, make a preliminary test as follows: Place the slider at the left-hand end of the slide-wire, touch the key momentarily, and note the direction of deflection. This test will permit the use of the *direction of deflection* as a guide in moving the slider to the balance point. Next locate the balance point *d*, Fig. 89, approximately and compute an approximate value of the unknown resistance. Remove plugs from the resistance box to make the known resistance nearly equal to this approximate value of the unknown resistance. When this has been done, the balance point will be near the middle of the slide wire.

(*a*) Determine the balance point several times carefully, moving the slider successively from left and from right until the un-shunted galvanometer shows no deflection.

(*b*) Reverse the current and repeat (*a*).

(*c*) Interchange the known and unknown resistances, and repeat (*a*) and (*b*).

(*d*) Proceed in like manner [(*a*), (*b*), and (*c*)] with each unknown resistance to be measured.

(*e*) Carefully measure the length of the slide wire.

Computations and results. — To derive a single result from the above observations for each of the unknown resistances proceed as follows: (1) Take the mean of the readings obtained under (*a*) and (*b*); (2) take the mean of the readings obtained under (*c*). Let l be the difference between (1) and (2), that is, the length of the wire between the two balance positions, and let L be the total length of the wire. Then the value of the ratio γ/δ derived from the complete set of observations is

$$\frac{L \pm l}{L \mp l}$$

Calculate the values of the unknown resistances and tabulate them with their identification numbers.

EXPERIMENT 65.

THE BOX BRIDGE.

The object of this experiment is to afford some practice in the use of the box form of Wheatstone's bridge without attempting to make allowance for the errors due to inaccuracies in the box bridge itself.

Theory. — The box form of Wheatstone's bridge includes three sets of resistances, namely, two sets γ and δ, Fig. 90, each consisting of, say, 10, 100 and 1,000 ohm coils, and one set β, which consists of, say, 1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, and 400 ohm coils. The sets of resistances γ and δ are used as the ratio arms of the bridge. The set β is called the rheostat and it is used as the known resistance. The two keys K and K' are sometimes arranged one above the other as a double contact

key so that K' may always be closed first and K afterwards. The letters *a*, *b*, *b'*, *c*, *d*, and *d'* represent binding posts; and the dotted lines represent connections outside of the box, α being the unknown resistance which is to be measured.

The particular ratio γ/δ should always be used which will

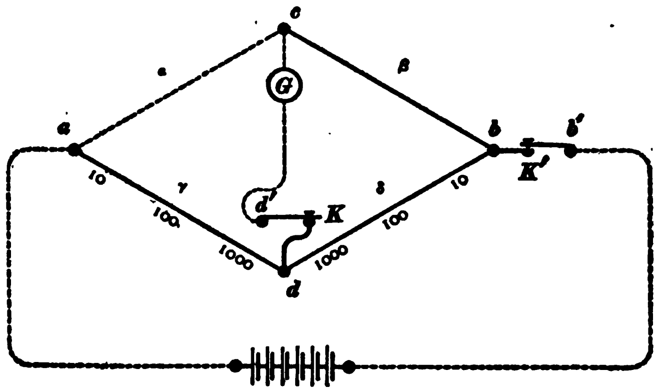

Fig. 90.

allow β to be between 100 ohms and 1,000 ohms so that β may include units, tens and hundreds. Thus if α is about 7 ohms the ratio of γ/δ should be $\frac{10}{1000}$ so that β may be about 700 ohms; if α is about 2,000 ohms the ratio γ/δ should be $\frac{1000}{100}$ so that β may be about 200 ohms.

Although the variations with temperature of the resistances of the coils of a good box bridge are usually negligible, it is usually quite important to note the temperature of the coil whose resistance is being measured.

Work to be done. — Make a diagram of the top of the box showing all connections. The internal connections are indicated by lines on the top of the box. Compare this diagram with Fig. 90, identify the various binding posts, the ratio arms, and the rheostat, and letter these as in the figure.

Connect two or three dry cells and one of the given* unknown

* The student should measure a moderately low resistance of two or three ohms, a medium resistance of several hundred ohms, and a high resistance of 50,000 or 60,000 ohms.

resistances to the bridge. With equal resistances in the ratio arms and zero resistance in the rheostat, make the preliminary test to determine which direction of deflection indicates too little resistance in rheostat.

In proceeding to find the correct value of β, try the larger resistances of the rheostat first. If it is found that the sum of all resistances in the rheostat is too small to balance the unknown resistance, change to the next larger ratio in the ratio arms: that is, take $\gamma/\delta = \frac{1000}{100}$. If this is found too small take the next ratio, and so on. If it is found that, with equal ratio arms, a small value of β will balance the unknown resistance, change to a smaller ratio in the ratio arms. In every case, make the ratio such as to use as large a value of β as possible.

It is usually impossible to balance a box bridge exactly, inasmuch as the smallest change in the value of β is, say, one ohm. Suppose, to take a particular case, that $\beta = 568$ is too small and that $\beta = 569$ is too large, as indicated by opposite deflections of the galvanometer, and suppose that the galvanometer deflection in the first instance is 26 scale divisions, and that the deflection in the second instance is 15 scale divisions. Then the correct value of β is $568 + 26/(15 + 26)$.

Proceed in this manner with each of the resistances to be tested. Observe the temperature of each resistance tested.

Computations and results. — The report should contain the lettered sketch of the box bridge, and the measured value and temperature of each resistance tested.

EXPERIMENT 66.

THE WATER COULOMBMETER.

The object of this experiment is to standardize * an ammeter by means of the water coulombmeter, or, as it is sometimes called, the water voltameter.

* The best method for standardizing an ammeter is by means of a standard resistance and a standard cell as explained in Experiment 84.

Theory. — When a solution of sulphuric acid is decomposed by the electric current between bright platinum electrodes, 0.174 cubic centimeter of mixed oxygen and hydrogen is liberated per ampere per second, the mixed gases being measured dry, at a temperature of 0° C., and at 760 millimeters pressure.

Work to be done. — Connect the ammeter, a lamp bank, and the coulombmeter in series to 110-volt direct-current supply mains through a double-pole switch. Make one or two preliminary runs so as to adjust the lamp bank to give the full ammeter reading, which should not exceed two or three amperes, and so as to determine the approximate time required to fill the measuring vessel with gas.

Make a blank tabular form for entering: (1) Exact time of closing circuit; (2) ammeter readings at intervals, say, of 30 seconds during a run; (3) exact time of opening circuit; (4) observed volume V of mixed gases; (5) difference in level between acid inside and outside of measuring vessel; (6) temperature t of mixed gases, and (7) barometer reading b in millimeters.

Make five runs, entering the above observations for each.

Computations and results. — The result required is the true value of current corresponding to the mean ammeter reading, the per cent. error of the ammeter and the reduction factor of the ammeter. This true current is found by reducing the observed volume of liberated gases to dry gas at 0° C. and 760 millimeters pressure and dividing this reduced volume by $0.174T$ where T is the mean duration in seconds of all the runs.

To reduce the observed volume use the formula:

$$\text{Reduced volume} = V \times \frac{273}{273 + t} \times \frac{p}{760}$$

The pressure p is given by the equation

$$p = b \pm \tfrac{1}{12} h - \tfrac{9}{10} e$$

where $\frac{1}{12}h$ is the difference of pressure outside and inside of the measuring vessel reduced to millimeters of mercury (the density

of the acid used is very nearly $\frac{1}{12}$ of the density of mercury), and e is the maximum pressure of water vapor over pure water at temperature t° C. (the pressure of water vapor over the sulphuric acid vapor is very nearly $\frac{9}{10}$ of e). The sulphuric acid used has a specific gravity of 1.13. The value of e may be taken from the following table:

VAPOR PRESSURE OF WATER VAPOR OVER PURE WATER.

Temperature Centigrade	5°	10°	15°	20°	25°	30°
Pressure in mm	6.5	9.1	12.7	17.4	23.5	31.5

EXPERIMENT 67.

CHEMICAL EFFICIENCY OF THE CHROMIC-ACID CELL.

The object of this experiment is to determine that fractional part of the zinc consumed in a chromic-acid cell which is consumed usefully, that is, in the production of current.

Theory. — The useful consumption of zinc in a voltaic cell is equal to the amount of zinc which would be deposited by the current delivered by the cell during the time that the cell is in operation.

The chemical efficiency of the cell is the ratio of useful zinc consumption to total zinc consumption. The efficiency of the cell will have different values for different values of current delivered by the cell, and the test of efficiency should be made for two or more values of current.

The total zinc consumption may be determined by weighing the zinc before and after using the cell.

The useful zinc consumption may be determined by calculation from the observed average current delivered by the cell, the time, and the electrochemical equivalent of zinc.

If it is not convenient to use an ammeter, a copper voltameter may be used and the useful consumption of zinc calculated from the weight of copper that is deposited by the current delivered by the cell.

Work to be done. — Set up the chromic-acid cell. Amalgamate the zinc by dipping it into dilute sulphuric acid and rubbing a little mercury over it. Then dry the zinc and weigh it. Do not lower the zinc into the solution until the circuit is all connected.

Connect the chromic-acid cell through an ammeter to a slide-wire resistance. Lower the zinc into the battery solution, note the clock reading, and quickly adjust the slide-wire resistance to bring the current to about 1.5 amperes. Take ammeter readings at intervals of one minute for half an hour; then lift the zinc, note the clock reading, wash and dry the zinc and weigh it.

Make tests in similar manner with about one ampere, and with one half ampere of current. The last weighing of the first test may be taken as the first weighing of the second, and so on. The zinc need not be re-amalgamated for the second and third tests.

Computations and results. — From the weighings of the zinc, find the total zinc consumption for each run. From the mean ammeter readings, the duration of the runs, and the electrochemical equivalent of zinc, calculate the useful consumption of zinc for each run. Then compute the efficiency of the cell for each value of current used.

EXPERIMENT 68.

Efficiency of an Electric Motor.

The object of this experiment is to determine the efficiency of an electric motor and incidentally to afford some practice in the handling of a motor and in the use of voltmeter and ammeter for measuring power.

Theory. — The power in watts delivered to an electric motor is the product of the electromotive force E between the supply mains multiplied by the current I delivered to the motor. The power in foot-pounds per minute delivered by a motor is equal to $2\pi nT$ where n is the speed in revolutions per minute and T is the torque developed by the motor in pound-feet.

The power delivered to the motor may be determined by meas-

uring E and I by means of a voltmeter and an ammeter, and the power delivered by the motor may be determined by taking the motor speed with a speed counter and measuring the torque by means of a brake. A suitable form of brake for a small motor is described in Experiment 30. If a motor of one or two horse-power is used a brake of the style shown in Fig. 91 may be employed, in which P represents the motor pulley. This pulley

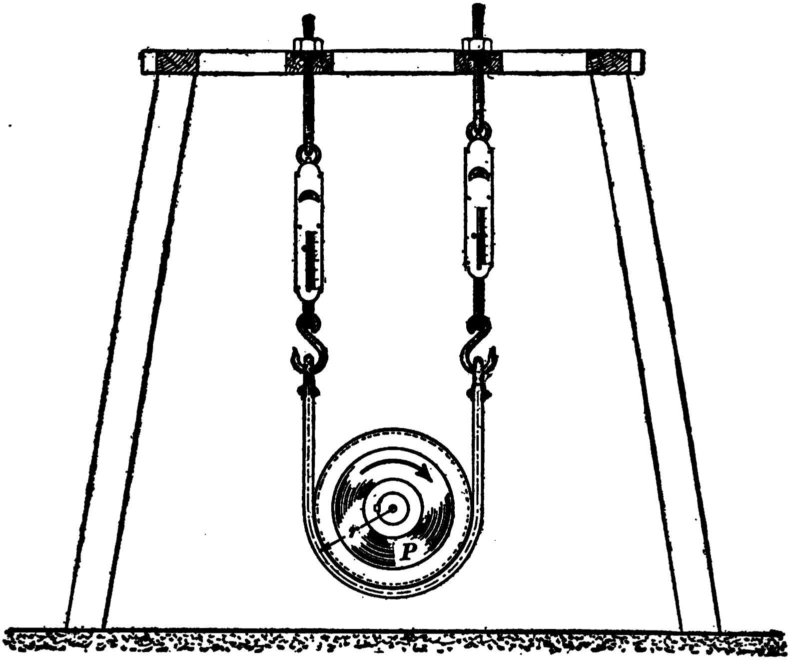

Fig. 91.

should be provided with a water flange so that water may be placed in the rim of the wheel to keep it cool.

The quotient, power output of motor divided by power intake of motor (output and input being reduced to the same denomination), is the efficiency of the motor.

Arrangement of apparatus. — The motor with its starting box is connected to the supply mains through the double-pole switch

S, and the ammeter A and voltmeter V are connected as shown in Fig. 92.

To start the motor loosen the brake strap, close the switch S, and move the arm of the starting box *slowly* to the running position. The object of the starting box is to connect resistance in series with the motor armature at starting and to cut this resistance out as the motor speeds up.

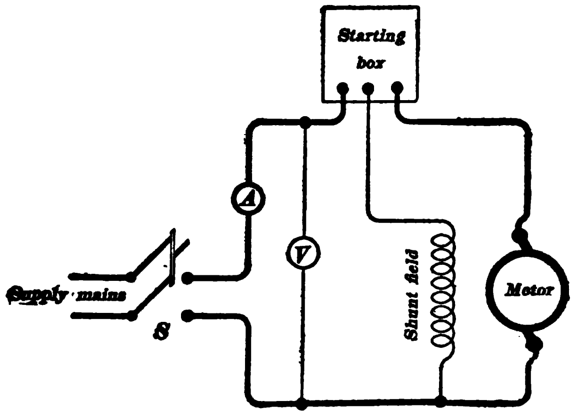

Fig. 92.

The full-load current of the motor is marked on its name plate.

Work to be done. — (*a*) Tighten the brake strap until the motor takes its full-load current. Then take a series of observations, taking the readings in the following order: Ammeter and voltmeter readings, dynamometer readings, speed of motor.

(*b*) Loosen the brake-strap until the motor takes three fourths of its full-load current and repeat the readings specified under (*a*).

(*c*) Loosen the brake-strap until the motor takes one half of its full-load current and read as before.

(*d*) Loosen the brake-strap until the motor takes one fourth of its full-load current and read as before.

(*e*) Measure the diameter of the motor pulley.

Computations and results. — Calculate the efficiency of the motor from each set of readings (*a*), (*b*), (*c*) and (*d*), and plot a

curve showing efficiencies as ordinates and fractions of full-load current as abscissas.

EXPERIMENT 69.

STANDARDIZATION OF GALVANOMETER. INSULATION RESISTANCE.

The object of this experiment is to standardize a galvanometer, and to use the standardized galvanometer to measure the current flowing through the insulation of a wire.

Standardization of galvanometer. — A galvanometer gives a deflection which is approximately proportional to the current; that is, we may write

$$i = kd \tag{i}$$

in which i is the current, d is the deflection which is produced, and k is a constant. This constant is called the *reduction factor* of the galvanometer, and to standardize the galvanometer is to determine the value of k. This is accomplished by observing the deflection produced by a known current.

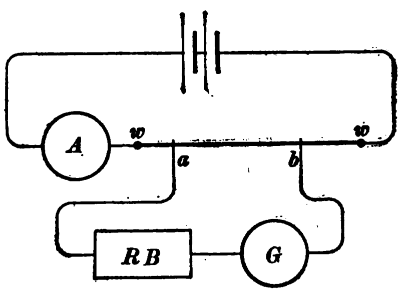

Fig. 93.

A bare german silver wire ww, Fig. 93, of which the resistance per centimeter is known, is stretched upon a board, and a known current, as measured by the ammeter A, is sent through the wire. The galvanometer G to be standardized is connected in series with a resistance box RB, and the galvanometer circuit is connected to two sliding contacts ab on the german silver wire. With zero resistance in the resistance box the points ab are adjusted until the galvanometer gives the largest readable deflection, and then resistance is inserted in the resistance box until the deflection is reduced to half. The resistance inserted in the resistance box is then equal to the resistance of the galvanometer. Let r be the known resistance of the portion ab of

the german silver wire, and let i be the known current flowing through the german silver wire. Then the electromotive force across ab is equal to ri and the current in the galvanometer is equal to ri divided by the resistance of the galvanometer circuit, so that the galvanometer deflection being observed, the value of the reduction factor k may be calculated. For the purposes of this experiment the reduction factor of the galvanometer need not be known with a greater accuracy than, say, five per cent. and the arrangement shown in Fig. 94 may be used instead of the arrangement shown in Fig. 87. A gravity cell B, Fig. 94, of which the electromotive force may be taken to be equal to 1.08 volts, is connected through a known resistance R' of 50 or 100 ohms so that the current through the wire ww may be determined by dividing the known electromotive force of the gravity cell by the approximately known resistance of the battery circuit.

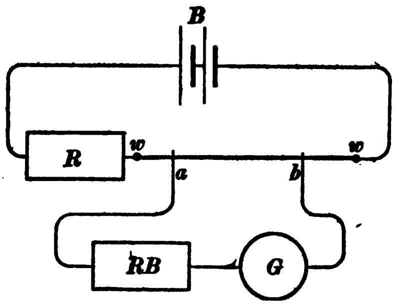

Fig. 94.

Insulation test. — (*a*) *Determination of the resistance of the walls of a glass beaker.* The beaker A is partly filled with water, and placed in a vessel of water V as shown in Fig. 95. A battery B, which gives an electromotive force of 100 volts or more, is connected to the water in the vessel V, through a known resistance R of several hundred thousand ohms, through the key K, through the galvanometer G, and wire W to the water in the beaker, as shown. In order to prevent the current which leaks over the surface of the beaker from flowing through the galvanometer, a strip of tin foil g is pasted around the beaker near the top and connected through the wire w as shown. The current which leaks over the surface of the beaker is then prevented from flowing through the galvanometer. The wire W must be insulated with extreme care, in fact, it should be sup-

ported on varnished glass standards; and the galvanometer G should stand upon glass insulators.

When the key K is closed the galvanometer gives a momentary throw due to the momentary pulse of current which charges the two walls of the beaker. Therefore, the key K is closed, the galvanometer is allowed to come to rest, and the steady de-

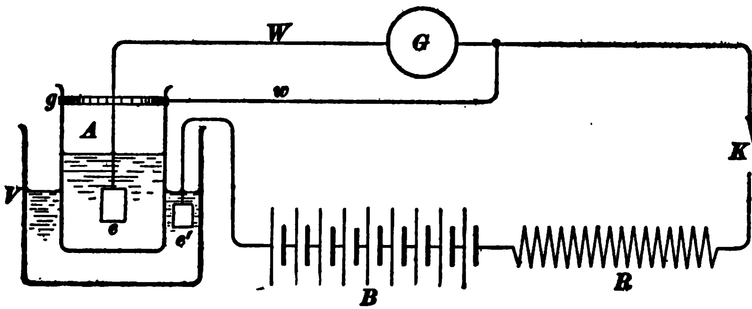

Fig. 95.

flection d is observed. The resistance of the galvanometer circuit may then be calculated from the known electromotive force of the battery B. The resistance of the walls of the beaker is so large that the resistance of the remainder of the circuit is entirely negligible in comparison, and therefore the resistance of the galvanometer circuit may be taken to be equal to the resistance of the walls of the beaker.

(*b*) *Determination of the insulation resistance of a wire.* — A measured length of the wire to be tested is coiled up and placed in a vessel of water V, as shown in Fig. 96, the ends of the insulated wire projecting above the water as shown. A guard wire g is wound around the ends of the insulation, and connected through the wire W as shown in the figure; and the wire W is connected to the metallic end of the insulated wire which is to be tested. In every essential respect, the arrangement in Fig. 96 is the same as the arrangement in Fig. 95, and the observations are taken in the same manner.

The insulation resistance of a wire varies greatly with the temperature and therefore the temperature of the water in the vessel *V* should be observed at the time the observations are taken.

The insulation resistance of a wire also varies greatly with the time that the wire has been submerged, and therefore this time should be specified.

Computations and results. — The report of this experiment should include:

(*a*) The reduction factor of the galvanometer as above determined.

(*b*) The resistance of the walls of the glass beaker, and the temperature of the beaker at the time, as determined above.

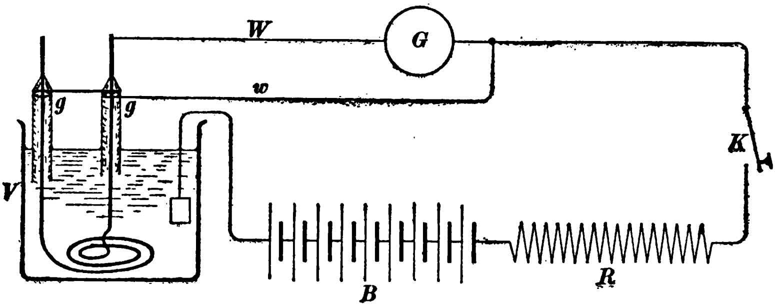

Fig. 96.

(*c*) The insulation resistance of the sample of wire, the temperature of the wire at the time, and the length of time the wire was submerged previous to the determination of its insulation resistance.

(*d*) The insulation resistance per mile of the sample of wire tested under (*b*) above is to be calculated from the observed resistance and length of the given sample.

EXPERIMENT 70.

Standardization of a Ballistic Galvanometer.

The object of this experiment is to familiarize the student with the two methods of standardizing a ballistic galvanometer: (*a*)

when it is used to measure the discharge of a condenser, and (*b*) when it is used to measure the impulse value of an induced electromotive force.

Theory. — The theory of the use of the ballistic galvanometer for the two purposes (*a*) and (*b*) is given on page 17.

Work to be done. (*a*) *Standardization of ballistic galvanometer for condenser tests.* — A standard condenser *C*, one or more standard cells *e*, the ballistic galvanometer *G*, and a highly insulated single-pole double-throw switch *S* are connected as shown in Fig. 97. An arrangement for controlling the movements of the galvanometer is also connected as explained on page 19. The number of standard cells should be chosen so as to give a moderately large throw of the galvanometer when the condenser is discharged through it.

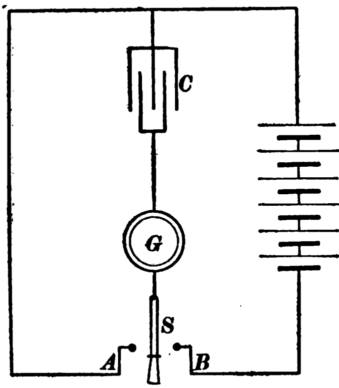

Fig. 97.

Throw the switch to the point *B* and observe the throw of the galvanometer produced by the pulse of current which flows into the condenser. Then throw the switch to the point *A* and observe the throw of the galvanometer due to the discharge of the condenser. These observations should be repeated ten times or more in order to eliminate erratic errors of observation and in order that the probable error of the result may be determined.

(*b*) *Standardization of ballistic galvanometer for the measurement of impulse values of electromotive forces.* — Connect the ballistic galvanometer, the exploring coil *X*, Fig. 86, which is to be used with the standardized galvanometer, and the secondary coil *SS*, Fig. 86, in series. Send a measured current *i* through the primary coil *PP*, and observe the galvanometer throw. Then bring the galvanometer to rest, and observe the galvanom-

eter throw when the current i is suddenly reduced to zero. These observations should be repeated ten or more times in order that erratic errors may be to some extent eliminated and in order that the probable error of the result may be determined.

Computations and results. — From each set of data obtained under (*a*) above, calculate the reduction factor k of the galvanometer as explained on page 17, find the average value of these results, and find the probable error of this final average.

From each set of data obtained under (*b*) above, calculate the value of k', as explained on page 19, find the average value of these results, and find the probable error of this final average.

EXPERIMENT 71.

Comparison of Capacities by the Ballistic Galvanometer.

The object of this experiment is to determine the capacity of a given condenser by comparing it with the capacity of a standard condenser.

Theory. — A condenser of capacity C is charged with an electromotive force E and discharged through a ballistic galvanometer; and the throw d of the galvanometer is observed. Then we have

$$q = CE = kd \tag{i}$$

Another condenser of capacity C' is charged with the same electromotive force, discharged through the ballistic galvanometer, and the throw d' of the galvanometer is observed. Then we have

$$q' = C'E = kd' \tag{ii}$$

Dividing equations (i) and (ii) member by member, we have

$$\frac{C}{C'} = \frac{d}{d'} \tag{iii}$$

from which the capacity C' may be calculated when C is known.

If the capacities C and C' are very different, if C' for ex-

ample is much larger than C, then the use of equation (iii) would involve the observation of a large throw d' and a small throw d, and the error in the observed value of the small throw would involve a very large percentage error in the ratio d/d'. To avoid this large error the condenser of small capacity should be charged with a large electromotive force, and the condenser of large capacity should be charged with a small electromotive force, so that the two throws d and d' may be nearly equal. Thus a number of dry cells, for example, may be connected in series for charging the small condenser to give the deflection d, and the individual cells or groups of cells may be used in succession for charging the large condenser; in which case the sum of the throws observed with the individual cells or groups of cells is to be used for d' in equation (iii).

Work to be done. — (*a*) Connect the standard condenser as indicated in Fig. 97, using a number of dry cells connected in series so as to give a large throw. Observe the throws of the galvanometer when the condenser is charged and when it is discharged, repeating the observations ten or more times.

(*b*) Connect the condenser of which the capacity C' is to be determined in place of the standard condenser in Fig. 97, and, having made a preliminary trial to find out how many of the cells formerly used should be used as a group to charge the condenser to give a large throw, arrange the cells used in (*a*) in such groups. Then with each of these groups observe throws of the galvanometer when the condenser is charged and when it is discharged, repeating the observations ten or more times.

(*c*) Note the capacity of the standard condenser.

Computations and results. — Calculate the capacity of the given condenser by means of equation (iii) using for d the average of all the throws observed under (*a*) above, and using for d' the sum of the averages of the throws obtained with the respective groups of cells under (*b*) above.

EXPERIMENT 72.

Study of Residual Charge.

The object of this experiment is to study the residual charge of a condenser.

Theory. — When an electromotive force is connected through a low resistance to a condenser, there flows into the condenser a sudden pulse of current which quickly drops to a small value and continues for some time, gradually falling to zero.* This small lingering current is called the *soaking-in* current.

When a charged condenser is connected to a low-resistance discharging circuit there flows out of the condenser a sudden pulse of current which quickly drops to a small value and continues for some time, gradually falling to zero. This lingering current is called the *soaking-out* current.

The lingering current that flows during the soaking in or out is usually too small to be observed directly; but when a condenser is momentarily connected to a low-resistance discharging circuit and then insulated, the soaking-out current accumulates in the condenser, constituting what is called the *residual charge*; and this may be observed by discharging the condenser a second time through a ballistic galvanometer.

Apparatus. — It is desirable to use a condenser of large capacity for this experiment and to charge it with a fairly large electromotive force,† and it is important to avoid sending full discharge of the condenser through the ballistic galvanometer. *The galvanometer is to be used only for measuring the residual charge as explained below.*

The apparatus is to be connected as shown in Fig. 98. A battery B of fairly large electromotive force is connected through a very high guard-resistance R, and the highly insulated single-

* There is, of course, some leakage current due to imperfect insulation. This leakage current is not considered in the above statement.

† The capacity of the condenser and the value of the charging electromotive force should be chosen so that the residual charge may give fairly large throws of the ballistic galvanometer.

pole double-throw switch S is arranged so that the condenser C may be charged, quickly discharged through the low resistance circuit A, and then insulated by leaving the switch S open. After residual charge has accumulated in the condenser for a specified time, the condenser may be discharged through the galvanometer G by closing the highly insulated single-pole switch S'.

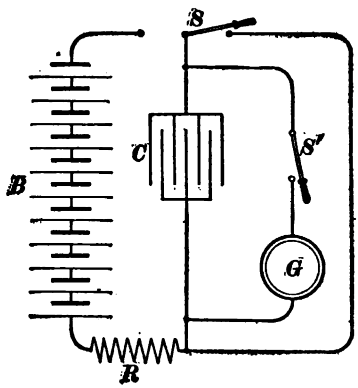

Fig. 98.

Be careful to avoid closing the switch S' until the initial charge on the condenser is discharged through the circuit A. The object of the guard-resistance R is to protect the galvanometer from damage by a chance closing of both switches S and S'.

Work to be done. — Make a preliminary test to determine what electromotive force must be used in charging the condenser in order that a fairly large throw of the ballistic galvanometer may be obtained when the condenser is charged for one minute, quickly discharged through the circuit A, Fig. 98, allowed to stand for one minute with the switch S open, and then discharged through the galvanometer by closing the switch S'.

Charge the condenser by connecting it for one minute to the battery B. Then discharge the condenser by connecting it momentarily through the circuit A, and allow it to stand for t seconds with the switch S open; then discharge the accumulated residual charge through the ballistic galvanometer by closing the switch S', and observe the throw. Repeat this procedure using the following values for t, namely, 3, 5, 10, 15, 20, 30, 40, 60, 90 seconds and so on until it is found that further increase of t causes a decreased throw of the ballistic galvanometer on account of leakage from the condenser.

Computations and results. — Plot a curve using the values of residual charge (throws of a ballistic galvanometer) as ordinates and soaking-out periods t as abscissas.

EXPERIMENT 73.

Charging and Discharging Curves of a Condenser.

The object of this experiment is to determine the relation between the charge in a condenser and the time that the charging battery is connected to the condenser through a very high resistance, or the time that the condenser is allowed to discharge through a very high resistance.

Theory. — A battery of electromotive force E is connected to a condenser through a high resistance R. At an instant, t seconds later, the condenser has received charge q and the electromotive force between the condenser terminals is q/C, where C is the capacity of the condenser. Therefore $E - q/C$ is the net electromotive force available for overcoming the resistance R, and the charging current dq/dt is by Ohm's law equal to this electromotive force divided by R.

That is,

$$\frac{dq}{dt} = \frac{E}{R} - \frac{q}{CR} \tag{i}$$

Let

$$x = \frac{E}{R} - \frac{q}{CR} \tag{ii}$$

Then

$$dx = -\frac{1}{CR} \cdot dq$$

and equation (i) becomes

$$-CR \cdot \frac{dx}{dt} = x$$

or

$$\frac{dx}{x} = -\frac{1}{CR} \cdot dt$$

whence

$$\log x = -\frac{1}{CR} \cdot t + \text{constant}$$

or

$$x = \text{constant} \times \epsilon^{-\frac{t}{CR}} \tag{iii}$$

Substituting value of x from (ii) in (iii) and solving we have

$$q = CE - \text{const} \times \epsilon^{-\frac{t}{CR}} \tag{iv}$$

Now when $t = 0$ the charge on the condenser is zero so that the constant in equation (iv) is equal to CE. Therefore

$$q = CE - CE \cdot \epsilon^{-\frac{t}{CR}} \tag{v}$$

in which q is the charge on the condenser t seconds after it is connected to a battery of electromotive force E, and R is the resistance of the charging circuit.

It may be shown in a similar manner that

$$q = CE \cdot \epsilon^{-\frac{t}{CR}} \tag{vi}$$

in which q is the charge which remains on the condenser t seconds after it had been connected to a discharging circuit of resistance R, CE being the initial charge.

Work to be done. — Make a preliminary test to determine what electromotive force must be used to charge the given condenser so that the discharge of the condenser may give a fairly large throw of the ballistic galvanometer. The battery B in Figs. 99 and 100 should give the electromotive force so found.

(*a*) *Charging curve of the condenser.* — Connect the condenser as shown in Fig. 99, R being a resistance of several millions of ohms. Charge the condenser for t seconds by throwing the single-pole switch S to the point a, and then quickly discharge through the galvanometer by throwing the switch to the point b and observe the throw. Repeat this procedure with values of t ranging from two seconds to 120 seconds or more.

(*b*) *Discharging curve of the condenser.* — Connect the apparatus as shown in Fig. 100, R being a resistance of several millions of ohms, as in Fig. 99. Charge the condenser by throwing the switch S to the point a, then open the switch, allow it to stand open for t seconds. Then discharge the condenser

by throwing the switch to the point *c*, and observe the throw of the ballistic galvanometer. Repeat this procedure for a series of values of *t* ranging from two seconds to about 120 seconds or more. The throws of the ballistic galvanometer in this case measure the values of charge left in the condenser after the con-

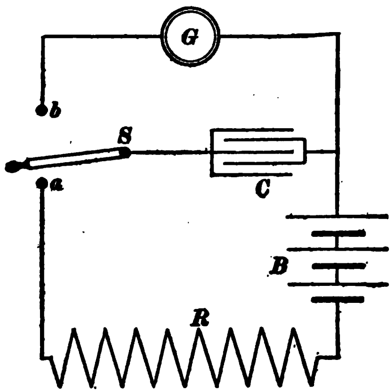

FIG. 99.

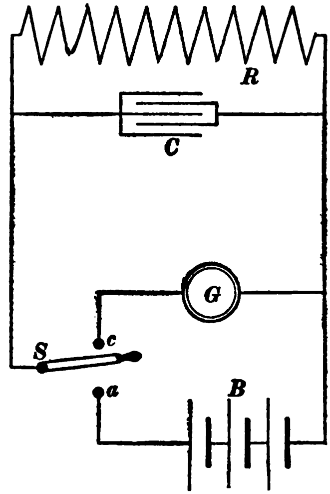

FIG. 100.

denser has been allowed to discharge for *t* seconds through the high resistance *R*.

Computations and results. — Plot on the same sheet of paper the charging and discharging curves of the condenser. For the charging curve use the values of *t* as abscissas, and the throws of the galvanometer observed under (*a*) above as ordinates. For the discharging curve, use the values of *t* as abscissas and the throws of the galvanometer observed under (*b*) above as ordinates.

EXPERIMENT 74.

DIP OF THE EARTH'S MAGNETIC FIELD.

The object of this experiment is to determine the angle of dip of the earth's magnetic field by means of the earth inductor and ballistic galvanometer.

Theory. — The earth inductor is a flat coil of wire mounted on an axis, the axis lying in the plane of the coil.

(*a*) Suppose the earth inductor is placed with its axis magnetic north and south, and with the plane of the coil horizontal. Then the amount of flux through the coil is equal to AV where A is the area of opening of the coil and V is the vertical component of the earth's magnetic field. If the coil is quickly turned through 180° the flux through the coil becomes $-AV$, since the flux now passes through the coil in the opposite direction. Therefore the total change of flux due to the turning of the coil through 180° is equal to $2AV$, and if Z is the number of turns of wire in the coil, *the impulse value of the electromotive force induced in the coil while it is being turned through 180° will be $2AVZ$.* See page 18.

(*b*) If the earth inductor is placed with its axis vertical and with the plane of the coil magnetic east and west, then the flux through the coil is AH, where H is the horizontal component of the earth's magnetic field, and if the coil is turned through 180° about the vertical axis the flux through the coil changes to $-AH$. *In this case, the impulse value of the electromotive force induced in the coil while it is being turned through 180° is equal to $2AHZ$.*

If the coil of the earth inductor is connected to a ballistic galvanometer then the throw d of the ballistic galvanometer produced when the coil is turned through 180°, as specified under (*a*) above, will be proportional to $2AVZ$; that is, we may write

$$2AVZ = k'd \tag{i}$$

In the same way, the throw d' of the ballistic galvanometer produced when the earth conductor is turned through 180°, as specified under (*b*) above, is proportional to $2AHZ$; that is, we may write

$$2AHZ = k'd' \tag{ii}$$

Dividing equation (i) by equation (ii) member by member, we have

$$\frac{V}{H} = \frac{d}{d'} = \tan \theta \qquad \text{(iii)}$$

in which θ is the angle of dip of the earth's magnetic field as shown by the diagram, Fig. 101.

Work to be done. — Connect the earth inductor to the ballistic galvanometer and proceed as follows:

(*a*) Place the earth inductor with its axis pointing magnetic north and south and with the plane of its coil horizontal. Bring the galvanometer to rest and observe its zero reading. Turn the coil quickly through 180° and observe the throw of the galvanometer. Bring the galvanometer to rest, turn the coil quickly back to its former position and again observe the throw. These observations should be repeated ten or more times.

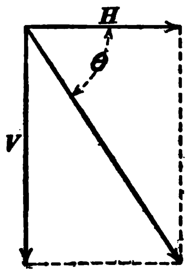

Fig. 101.

(*b*) Place the earth inductor with its axis vertical and the plane of its coil magnetic east and west, and take a series of observations as specified under (*a*), turning the coil back and forth through 180°.

Computations and results. — From the mean values d and d' of the throws observed under (*a*) and (*b*) above, calculate the angle of dip of the earth's magnetic field.

EXPERIMENT 75.

Distribution of Flux along a Magnet.

The object of this experiment is to investigate the distribution of flux along a bar magnet, by means of an exploring coil and ballistic galvanometer.

Theory. — Figure 102 shows the lines of force in the neighborhood of an ordinary bar magnet. These lines of force are considered to trend inwards towards the south pole of the magnet, through the magnet, and outwards from the north pole, and the total flux across a section of the magnet at a is equal to the

total flux which emanates from the north pole to the right of a in the figure. Thus at the center of the bar the flux *through the bar* is a maximum and it decreases towards the ends. The poles of the magnet are the regions where lines of force leave the iron (north pole) or enter the iron (south pole), and if the poles were concentrated at the ends of the bar the flux through the bar would be the same from end to end.

If a small exploring coil of wire surrounding the magnet at a, Fig. 102, be connected to a ballistic galvanometer, then quickly pulled off and moved to a distance from the magnet, the resulting

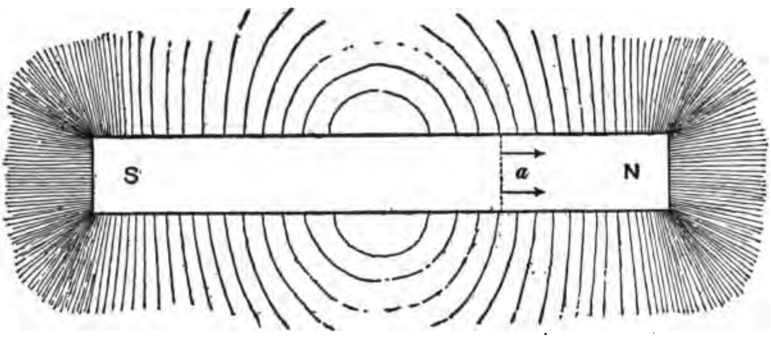

Fig. 102.

galvanometer throw is proportional to the magnetic flux Φ which passes through the magnet bar at a.

Apparatus and work to be done. — A bar magnet a foot or more in length, and of small cross-section, should be used for this experiment. The exploring coil should be as compact as may be, and should have an opening little greater than the cross-section of the magnet.

Connect the exploring coil to the galvanometer by means of a flexible lamp-cord. Place the coil upon the magnet as near the end of the bar as may be. Bring the galvanometer to rest, and observe its zero reading. Pull the coil off quickly, and observe the throw of the galvanometer. Take observations in the same manner at positions half an inch apart, until the middle of the bar has been reached. Repeat two or more times.

Computations and results. — Plot a curve using lengths along the bar as abscissas and the mean of the corresponding throws as ordinates. This curve represents the distribution of flux *within the bar.* Plot the curve using lengths along the bar as abscissas, and differences of successive throws as ordinates. In this curve let the first throw taken be the ordinate at the end of the bar. This curve represents the distribution of flux *emanating from the bar.*

EXPERIMENT 76.

Determination of Dielectric Strengths.

The object of this experiment is to determine dielectric strength of several insulating substances by means of the spark gauge.

Theory. — The spark gauge consists of a pair of smooth metal spheres with an air gap between them. The length of the gap is indicated by a scale or a micrometer screw.* The following table gives the electromotive forces required to spark across various lengths of air gap between polished brass spheres.†

Table of Sparking Voltages in Air Between Polished Brass Spheres.

S = length of gap. d = diameter of spheres.

S in cm.	d = 1.0 cm.	d = 2.0 cm.	d = 6 0 cm.
0.02	1,560	1,530	....
0.04	2,460	2,430	....
0.06	3,300	3,240	....
0.08	4,050	3,990	....
0.10	4,800	4,800	4,500
0.20	8,400	8,400	7,800
0.30	11,400	11,400	10,800
0.40	14,400	14,400	13,500
0.50	17,100	17,100	16,500
0.60	19,500	19,800	19,500
0.70	21,600	22,500	22,500
0.80	23,400	24,900	26,100
0.90	24,600	27,300	29,400
1.00	25,500	29,100	32,700

* In the standard form of spark gauge for commercial electrical testing, the spark gap is between two very sharp needle points, as described on page 43, Vol. 2, *Elements of Electrical Engineering*, by Franklin and Esty.

† Heydweiller, Wied. Ann., Vol. 48, page 235, 1893. The table gives the sparking distances at 18° C. and 745 millimeters pressure. The sparking distances increase one per cent. for each 3° drop in temperature or for each 8 millimeters rise in pressure.

In using the spark gauge the insulating material to be tested is placed in the form of a thin sheet between two flat metal plates, and these plates are connected in parallel with the spark gauge. A high electromotive force from a Holtz machine or induction coil is then connected to the terminals of the spark gauge, and the spheres are slowly moved apart until the spark ceases to jump between them, having punctured the insulator. The length of the spark gap between the spheres is then noted and the corresponding electromotive force, as taken from the above table, is divided by the thickness of the insulating material to give its dielectric strength.

In many cases the electromotive force required to puncture a layer of insulating material is not even approximately proportional to its thickness. In such cases, the dielectric strength of the material is specified as so many volts required to puncture a specified thickness of the material.

Work to be done. — Test the dielectric strength of the insulation of several samples of wire, of oiled and waxed paper, and of paraffine oil.

(*a*) Wrap a small piece of tin foil around a wire to be tested. Connect this tin foil to one terminal of the spark gauge and connect the wire itself to the other terminal of the spark gauge. Start the electric machine and determine the length of spark gap corresponding to the puncture of the insulation of the wire. Note the kind of insulating material on the wire, and determine its approximate thickness by measuring the diameter of the bare wire and the diameter of the wire and insulation.

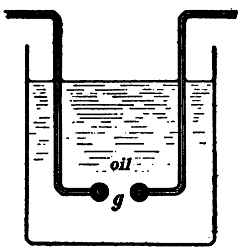

Fig. 103.

(*b*) *Paper.* — Place several thicknesses of the paper between flat plates as above explained, and measure the spark gap of the gauge corresponding to the puncture of the paper. Note the kind of paper and character of the impregnation, and measure the thickness of the paper.

(*c*) *Oil.* — An adjustable spark gap between the brass knobs is arranged as shown in Fig. 103, the length of the spark gap being determined by measuring the movement of the rods above the oil. Set the spark gap in the oil at various measured lengths and determine the corresponding spark gaps of the gauge for which the spark strikes across in the oil.

Computations and results.— From the data obtained under (*a*) and (*b*) above, compute the dielectric strengths of the various insulating materials in volts per centimeter. From the data obtained under (*c*) above plot a curve of which the abscissas represent lengths of gaps in oil and the ordinates represent voltages required to puncture the gaps.

EXPERIMENT 77.

THERMO-ELECTRIC STUDY.

The object of this experiment is to determine the curve showing the relation between the electromotive force e of an iron-zinc thermo-element and the temperature T of one junction, the other junction being kept at 0° C.; and to determine the values of the constants a, b, and c in the equation

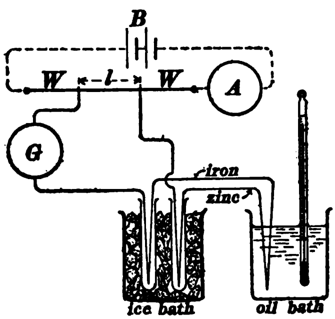

Fig. 104.

$$e = a + bT + cT^2 \qquad \text{(i)}$$

Apparatus. — The arrangement of the apparatus is shown in Fig. 104. One junction of the iron-zinc element is submerged in an oil-bath, and the points of attachment of the copper connecting wires to the iron and zinc strips are then placed in two test-tubes filled with oil and submerged in an ice-bath, as shown in the figure. The values of the electromotive force e are measured by a D'Arsonval galvanometer G, the circuit of which includes a measured length l of a slide wire WW of which the resistance per unit length is known. An am-

meter A and a battery B are arranged so that a known current i may be sent through the slide wire. Let r be the known resistance of the portion l of the slide wire; then the electromotive force acting on the galvanometer circuit due to the current i is equal to ri. By observing the deflection due to this known electromotive force the galvanometer is standardized, so that the electromotive force corresponding to any deflection may be calculated.

Work to be done. — Set up the apparatus as shown in Fig. 104 and take the observations for standardizing the galvanometer.

Heat the oil-bath slowly, keeping it well stirred and take simultaneous readings of the thermometer and of the galvanometer. These readings should be taken while the temperature is rising and again while the temperature is falling.

Caution. — Should the oil-bath catch fire, remove the thermometer instantly, turn off the gas and have a board handy for clapping over the metal vessel which contains the oil. Heavy mineral oil may be heated to 300° or 360° C.

Be very careful to avoid heating the oil-bath above the highest temperature indicated by the thermometer. To do this will break the thermometer.

Note. — The greatest electromotive force of the iron-zinc element under the above conditions will be about 3,000 microvolts, and the resistance of the galvanometer circuit should be adjusted so that this electromotive force will produce the largest readable deflection. This adjustment can best be made while the galvanometer is being standardized. Thus, if the resistance r is, say, 1/200 ohm, the current i to give 3,000 microvolts between the terminals of r must be 600 milliamperes.

Computations and results. — (*a*) Plot the observed values of e and T.

(*b*) Calculate the values of the constants a, b, and c in equation (i).

(*c*) Find the thermo-electric power * of iron-zinc at 0° C.

(*d*) Find the neutral temperature * of iron and zinc.

* See Nichols and Franklin's *Elements of Physics*, Vol. 2, pages 139 to 144.

EXPERIMENT 78.

Comparison of Magnetic Fields by Deflections.

The object of this experiment is to compare the intensities of the horizontal component of the earth's magnetic field at several places in the laboratory.

Theory. — A small magnet *ns*, Fig. 105, is suspended by a fine silk fiber at the point where the horizontal component of the earth's field has an intensity H. (The plane of the paper in Fig. 105 is supposed to be horizontal.) The magnet comes to rest with its north pole pointing in the direction of H. A large

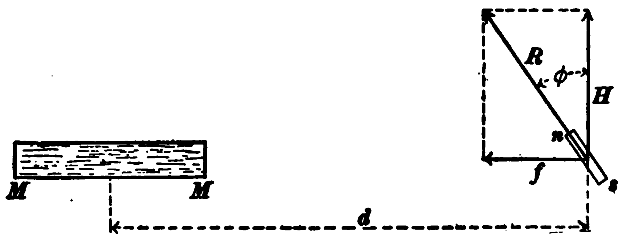

Fig. 105.

magnet MM is then placed at a measured distance d due magnetic east or west of the small magnet, as shown in the figure. This large magnet produces a field of definite intensity f at the place where the small magnet is suspended, and the small magnet then turns into the direction of the resultant field R. The angle ϕ may be determined by observing the position of the small magnet before and after the large magnet is placed in position. From the parallelogram of Fig. 105, we have

$$\tan \phi = \frac{f}{H} \qquad \text{(i)}$$

The small magnet is then suspended at another point at which the horizontal component of the earth's magnetic field is H', and the large magnet MM is placed at the same distance from it due magnetic east or west as before. In this case the deflection

ϕ' of the suspended magnet may be observed, giving the equation

$$\tan \phi' = \frac{f}{H'} \tag{ii}$$

Dividing equation (i) by equation (ii), member by member, we have

$$\frac{H'}{H} = \frac{\tan \phi}{\tan \phi'} \tag{iii}$$

from which the ratio of H'/H is known when the two deflections have been observed.

Apparatus. — The small magnet *ns* is suspended over a divided circle, and a slender pointer is attached to the magnet so as to enable the angle of deflection of the magnet to be observed, exactly as in the compass of a tangent galvanometer. This com-

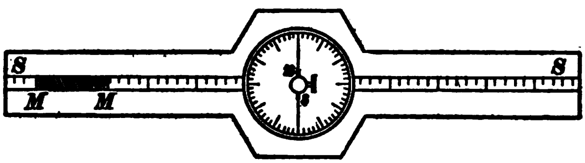

Fig. 106.

pass box is mounted on a board upon which are fixed two wooden scales by means of which the distance d may be read off. This apparatus is called a magnetometer. A top view of this magnetometer is shown in Fig. 106.

Work to be done. — Let A, B, C, etc., be the places at which the values of H are to be compared. Place the magnet at A with the scale SS due magnetic east and west, as indicated by the readings of the pointer which is attached to the suspended magnet. All movable pieces of iron including the large magnet MM must be at a considerable distance from A during this adjustment.

Place the large magnet to the east of the compass box at a definite distance d such as to give a deflection of about $45°$ of the suspended magnet. Observe the distance d and read both

ends of the pointer. Turn the magnet *MM* end for end, leaving d the same as before, and again read both ends of the pointer. Place the magnet *MM* to the west of the compass box and at the same distance d and read both ends of the pointer. Turn the magnet *MM* end for end and again read both ends of the pointer. The average of the eight readings thus taken gives the value of the angle of deflection ϕ.

Set up the magnetometer at each of the other points B, C, etc., and take observations exactly as above for determining ϕ', ϕ'', and so on, the distance d being the same in all cases.

Computations and results. — From the data obtained, calculate the ratios H'/H, H''/H, and so on. If the value of H is known at one place, compute the values for the other places.

EXPERIMENT 79.

Comparison of Magnetic Fields by Oscillations.

The object of this experiment is to determine the relative intensities of the horizontal component of the earth's magnetic field at several points in the laboratory by observing the period of oscillation of a suspended magnet.

Theory. — A suspended magnet sets itself parallel to the magnetic field in which it is placed. If the magnet is displaced from this position of equilibrium (about the vertical axis of suspension) it oscillates to and fro and we have

$$\frac{4\pi^2 K}{\tau^2} = MH \tag{i}$$

in which τ is the period of one complete oscillation in seconds, K is the moment of inertia of the magnet bar and stirrup, M is the magnetic moment of the magnet, and H is the horizontal component of the earth's magnetic field.

If the same magnet is suspended at another place where the horizontal component of the earth's magnetic field is H' we have

$$\frac{4\pi^2 K}{\tau'^2} = MH' \qquad \text{(ii)}$$

in which τ' is the new period of oscillation. Dividing equations (1) and (2) member by member, and transposing, we have

$$\frac{H'}{H} = \frac{\tau^2}{\tau'^2} \qquad \text{(iii)}$$

The value of H' may be computed from equation (iii) when H is known and τ and τ' have been determined.

Apparatus. — The large magnet *MM* of Experiment 78 is suspended in a glass case by a long fiber of unspun silk as shown in Fig. 107. At the top of the suspension tube means is provided for lowering the magnet to the floor of the case when it is to be carried about. One end of the magnet should have a white mark on it in order that it may be clearly seen in the field of a sighting telescope which is to be sighted upon it when at rest. The cross-hair of the telescope is to be used as a reference line in observing the oscillations of the magnet.

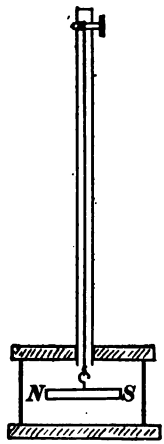

Fig. 107.

Work to be done. — Let A, B, C, etc., be the places at which the values of H are to be compared. Set up the arrangement shown in Fig. 107 at A, carefully raise the magnet from the floor of the case, and bring it to rest. Oscillations about the axis of suspension may be eliminated by properly moving a magnet outside the case. Pendulous oscillations may be eliminated as follows: Touch the top of the suspension tube lightly with the finger as the magnet swings towards the hand, and remove the finger before the return swing. Repeat this operation, keeping in unison with the swings until the fiber hangs motionless.

Place the telescope due magnetic north or south of the suspended magnet, and sight it upon the end of the magnet. Then

set the magnet swinging through a small angle by properly manipulating a magnet outside the case. Determine the time of vibration of the magnet by noting the exact number of seconds required for 20 or more oscillations, as explained in Vol. I, page 31, example (*b*).

Set up the apparatus in the similar manner at each of the other places and determine the time of oscillation as above.

Computations and results. — Compute the values of H'/H, H''/H, and so on. If the value of H is known for one place, compute the values for the other places.

EXPERIMENT 80.

Determination of H by Gauss's Method.

The object of this experiment is to determine the horizontal intensity of the earth's magnetic field at a given point by means of Gauss's method.

Theory. — (*a*) A large magnet MM is placed at a distance d and then at a distance d_1 due magnetic east or west of a small suspended magnet as described in Experiment 78, and the corresponding deflections ϕ and ϕ_1 of the small magnet are observed. If the large magnet MM is moderately short as compared with the distances d and d_1, the following equation * is very approximately true:

$$\frac{M}{H} = \frac{d^5 \tan\phi - d_1^5 \tan\phi_1}{2(d^2 - d_1^2)} \qquad \text{(i)}$$

in which M is the magnetic moment of the large magnet, and H is the horizontal intensity of the earth's field at the point at which the small magnet is suspended.

(*b*) The large magnet MM is then suspended at the place formerly occupied by the small magnet, set vibrating about a

* For derivation of this equation see *Absolute Measurements in Electricity and Magnetism*, by A. Gray, Vol. 2, Part 1, pages 69 to 100, London, Macmillan & Company, 1893.

vertical axis, and its period of oscillation is observed as explained Ein xperiment 79. Then we have

$$MH = \frac{4\pi^2 K}{\tau^2} \qquad \text{(ii)}$$

in which K is the moment of inertia of the magnet MM about the axis of suspension and τ is the period of its oscillation. The value of K may be calculated from the mass and dimensions of the magnet.

The unknown magnetic moment M may be eliminated between equations (i) and (ii) and the value of H determined in terms of the observed values of the remaining quantities.

Work to be done. — (*a*) Set up the magnetometer, Fig. 106, at the place where the value of H is to be determined, and observe the angles ϕ and ϕ_1 corresponding to distances d and d_1 as explained in Experiment 78.

(*b*) Suspend the large magnet as shown in Fig. 107, put it in place of the magnetometer, and observe the time of vibration of the magnet as explained under Experiment 79.

(*c*) Weigh the large magnet MM, and measure its length and breadth, in order that its moment of inertia may be determined by calculation.

Computations and results. — From the data obtained under (*c*) above, calculate the moment of inertia K of the magnet. Substitute the observed values of d, d_1, ϕ, ϕ_1, and τ, and the calculated value of K in equations (i) and (ii), and calculate the value of H.

PART V.

ADVANCED ELECTRICAL MEASUREMENTS.

LIST OF EXPERIMENTS.

81. Standardization of an ammeter by the copper coulombmeter.

82. Standardization of an ammeter by means of a standard resistance and a standard cell.

83. Standardization and calibration of a voltmeter.

84. Standardization and calibration of an ammeter.

85. The A.C.–D.C. comparator.

86. Study of a Siemens electrodynamometer.

87. Standardization and calibration of a wattmeter.

88. Standardization and calibration of a watt-hour meter.

89. Comparison of resistance standards by Carey-Foster's method.

90. Errors of a resistance box.

91. Measurement of low resistance by the Kelvin double bridge. Conductivity test of copper wire.

92. Temperature coefficient of resistance of a sample of wire.

93. Insulation test.

94. Specific resistance of electrolytes.

95. Primary battery tests.

96. Magnetic test of iron. Ewing's method.

97. Magnetic test of iron. Rowland's method.

98. Measurement of intense magnetic field by the ballistic galvanometer.

99. Comparison of electrostatic capacities. Method of mixtures.

100. Measurement of insulation resistance by leakage.

101. Comparison of inductances by Wheatstone's bridge. The secohmmeter.

102. Comparison of capacities by Wheatstone's bridge.

103. Study of electrolytic polarization. Decomposition voltages.

104. Use of the normal electrode for determining electrolytic polarization.

105. Determination of relative migration velocities. Hittorf's ratio.

106. Absolute determination of migration velocity.

107. Study of radio-activity.

108. A study of radio-active transformation.

EXPERIMENT 81.

Standardization of an Ammeter by the Copper Coulombmeter.

The object of this experiment is to standardize an ammeter by means of the copper coulombmeter.

General discussion. — The silver coulombmeter, the use of which is described on page 10, affords the most accurate means for measuring current for the purpose of standardizing an ammeter. The use of a standard resistance and a standard cell is the most convenient method for standardizing an ammeter (see Experiments 82 and 83), and it comes next to the silver coulombmeter in point of accuracy. The copper coulombmeter is much more frequently used than the silver coulombmeter, being much cheaper. For approximate results the water coulombmeter is used as described in Experiment 66.

The copper coulombmeter is less accurate than the silver coulombmeter, partly because the electrochemical equivalent of copper is less than that of silver, so that the amount of copper deposited by a given current in a given time is correspondingly less, partly because of the slow dissolving of metallic copper in the copper sulphate solution which is used as the electrolyte, and partly because of the oxidation of the copper deposit and the consequent increase of weight of the plates during the process of washing and drying.

Directions for manipulating the copper coulombmeter. — The electrolyte used is a solution of copper sulphate having a density of 1.15 to 1.18, with 1 per cent. of free sulphuric acid. After continued use the acid becomes exhausted by action on the plates, and more acid should be added.

The loss plates, the anodes, should never be smaller than about 40 square centimeters of area per ampere of current; otherwise the resistance of the cell varies greatly.

The gain plate, the cathode, should have an area of from 50 to 100 square centimeters per ampere of current, and it should have a narrow neck or necks where it passes through the surface of the electrolyte, as shown in Fig. 108. For large currents, a number of gain plates may be used alternating with the loss plates.

Use a new and undented piece of thin sheet copper for the gain plate. Make the corners round and smooth so as to avoid the growth of detachable crystals of copper; polish both sides of the copper sheet thoroughly with sand-paper, wash in cold water, rub with a clean cloth free from oil, dry at a gentle heat, cool and weigh. It is very important in the handling of the gain plate to avoid touching it with the fingers. In cleaning the plate it should be laid upon a fresh piece of clean paper, and the hands should be washed with soap and rinsed thoroughly so as to avoid the traces of oil which would otherwise be transferred to the copper sheet from the hands by the sand-paper and cloth.

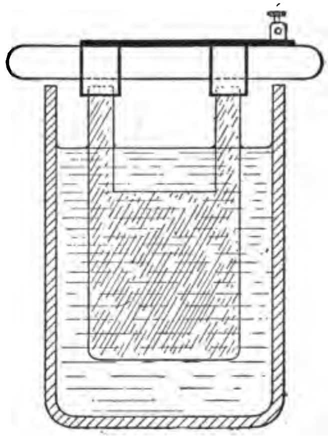
Fig. 108.

After the deposition of the copper is finished, lift the gain plate out of the solution and place it immediately into a vessel containing very dilute sulphuric acid. Then rinse thoroughly with distilled water, dry quickly between folds of clean filter paper, warm the plate very slightly to drive off the remaining moisture, cool, and weigh.

Connect the ammeter to be tested, in series with the copper voltmeter and a convenient switch, to a storage battery * with several ohms of metallic resistance in circuit. The battery should be allowed to give current through an auxiliary circuit for several

* A dynamo always gives a pulsating current and, especially in the standardization of an alternating-current ammeter such as an electrodynamometer, it should not be used.

minutes before the observations are begun so that its electromotive force may settle to a more or less steady value. As soon as the gain plate is weighed and in position, close the switch and observe the clock reading. Then observe the ammeter readings at intervals of thirty seconds for half an hour, and again observe the clock reading when the switch is opened. Then remove the gain plate, wash, dry, and weigh as directed above.

From the weighed deposit of copper, calculate the average current during the test. This average current corresponds to the average ammeter reading.

The electrochemical equivalent of copper varies with the temperature of the electrolyte and with the current density as shown by the following table which is from the experiments of Mr. A. W. Meikle. Where accurate results are required, it will be necessary to compute the current density in order to refer to the table. If the ammeter is direct-reading, the ammeter reading may be used in determining the current density. If not, an approximate value of current must be computed from the weighings, using an approximate value of electrochemical equivalent.

TABLE.

ELECTROCHEMICAL EQUIVALENTS OF COPPER.

Sq. cm. of Cathode per Ampere.	12° C.	23° C.	28° C.
50	.0003288	.0003286	.0003286
100	.0003288	.0003283	.0003281
150	.0003287	.0003280	.0003278
200	.0003285	.0003277	.0003274
250	.0003283	.0003275	.0003268
300	.0003282	.0003272	.0003262

EXPERIMENT 82.

STANDARDIZATION OF AN AMMETER BY MEANS OF A STANDARD RESISTANCE AND A STANDARD CELL.

The object of this experiment is to standardize an ammeter by means of a standard resistance and a standard cell.

Apparatus. — A storage battery *B*, Fig. 109, produces a

current in a circuit which contains an adjustable resistance R, an ammeter A, which is to be tested, and a standard resistance S. The standard resistance S must be able to carry the desired

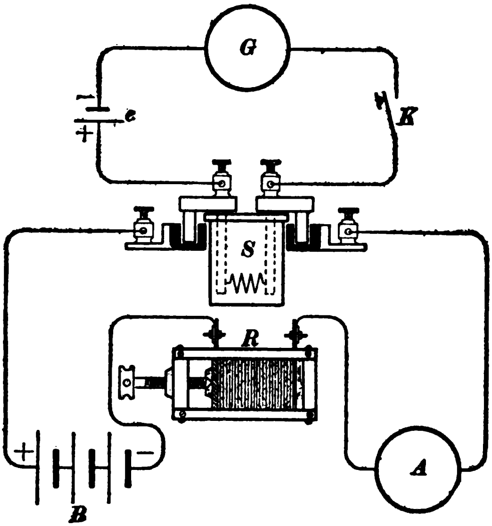

Fig. 109.

current without being perceptibly heated and its value must be sufficiently great to give across its terminals an electromotive force equal to the electromotive force of one or two standard cells.* A standard cell e and a sensitive galvanometer G are connected to the auxiliary binding posts of the standard resistance, as shown in the figure, and the resistance R is adjusted until the current through A and S is such that the electromotive force across S is exactly equal to the electromotive force of the standard cell as indicated by the absence of deflection of the galvanometer when the key K is closed. The current through A and S is then equal to e/r, where e is the electromotive force of the standard cell and r is the resistance of S.

* This condition makes it very awkward in many cases to apply the method described in this experiment to the standardizing of an ammeter. The best method by far is that which is described in Experiment 84 in which a potentiometer is used for measuring electromotive force across the standard resistance.

Great care must be taken to avoid closing the circuit of the standard cell e when any considerable current is likely to flow through it. Therefore, a high resistance should be in circuit with the standard cell while the preliminary adjustments are being made; this high resistance may be short-circuited when the final adjustments are made. The key K should never be closed for a longer time than is barely sufficient to show the direction of deflection of the galvanometer.

The standard resistance S should be submerged in an oil-bath, and its temperature should be indicated by a properly placed thermometer. The resistance of S together with its temperature coefficient of resistance may be found in the laboratory records.

The electromotive force of the standard cell is as specified on page 12. The temperature of the cell should be noted in order that its electromotive force may be determined.

EXPERIMENT 83.

Standardization and Calibration of a Voltmeter.

The object of this experiment is to afford an exercise in the use of the potentiometer for the accurate measurement of electromotive force.

Theory. — The potentiometer consists of a subdivided resistance box which is connected to an auxiliary battery so that a constant current flows through it. (*a*) The two points on the box are found between which the electromotive force is equal to the electromotive force e of a standard cell and the intervening resistance r is read off. (*b*) The two points on the box are found between which the electromotive force is equal to the electromotive force E to be measured and the intervening resistance R is read off. Then $e/E = r/R$ whence E is known.

Apparatus. — The simplest form of potentiometer is the slide-wire potentiometer as described in Experiment 63, in which the two resistances, r and R above-mentioned, are the resistances of portions of a slide-wire. If a resistance box is used instead of a slide-wire, then it is only possible to adjust the values of r and

R in steps, and a special device is necessary to overcome this difficulty.

In the potentiometer of Otto Wolff the following device is used: The auxiliary battery B, Fig. 110a, produces a constant

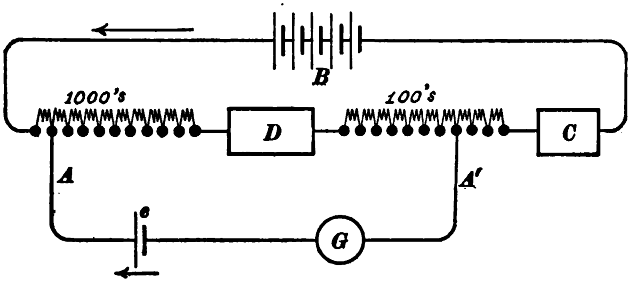

Fig. 110a.

current through a circuit of constant resistance. The circuit which contains the sensitive galvanometer G and standard cell e is connected to movable arms A and A' which play over a series of contact points so as to include any desired number of thousand-ohm coils and any desired number of hundred-ohm coils between the two points of contact of the galvanometer circuit, thus enabling r or R to be adjusted to any number of thousands and hundreds of ohms. In order to adjust r or R by steps of 10 ohms, a device is arranged for inserting 10-ohm coils at D and at the same time taking 10-ohm coils out of circuit at C, or vice versa. A similar arrangement is used in adjusting r or R by 1-ohm steps and by 0.1-ohm steps. The details of the device for inserting coils at D and taking coils out at C, or vice versa, are shown in Fig. 110b. Two sets CC and DD of resistances each containing ten 10-ohm coils are arranged between contact points as shown. The circuit through D, Fig. 110a, is from d to d' in Fig. 110b, any number of 10-ohm coils being included according to the position of the connector s. The circuit C, Fig. 110a, is from c to c', Fig. 110b, and it includes any number of 10-ohm coils according to the position of the connector s'. The two connectors s and s' are carried on the pivoted arm A'' as shown in the figure, so that a 10-ohm

coil is cut out between c and c' every time a 10-ohm coil is included between d and d', or vice versa. A top view of the

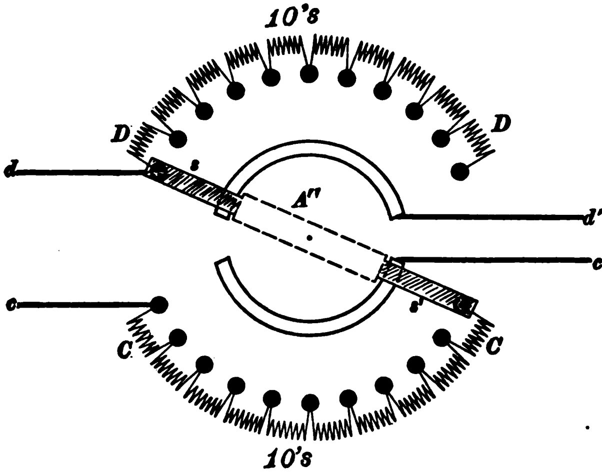

Fig. 110b.

Wolff potentiometer is shown in Fig. 110c. The auxiliary battery B, Fig. 110a, is connected to the binding posts B in Fig. 110c,

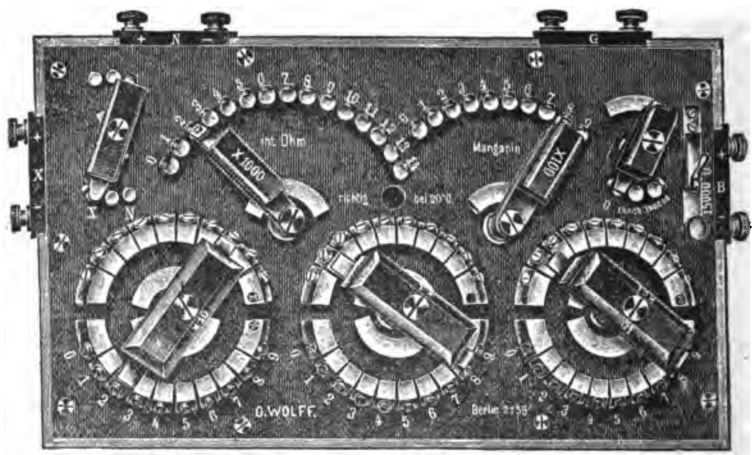

Fig. 110c.

a resistance box usually being connected in the battery circuit. The standard cell e, Fig. 110a, is connected to the binding posts

N in Fig. 110*c*. The galvanometer G in Fig. 110*a* is connected to the binding posts G in Fig. 110*c*, and the electromotive force to be measured is connected to the binding posts X in Fig. 110*c*. The switch at the upper left-hand corner in Fig. 110*c* is for connecting either the standard cell N, or the unknown electromotive force X into the galvanometer circuit. The switch at the upper right-hand corner is for connecting more or less resistance in series with the galvanometer and standard cell during the preliminary adjustment of the apparatus.

To measure an electromotive force with the Wolff potentiometer proceed as follows: (*a*) For electromotive forces of 1.5 volts or less. The battery B, Fig. 110*a*, should in this case have about 1.5 volts electromotive force and it should be connected through an auxiliary resistance box to the B posts of the potentiometer. Note the temperature of the standard cell and determine its exact voltage (see page 12). Set the thousands', hundreds', tens', units', and tenths' arms of the potentiometer to indicate the successive digits in the number which expresses the known electromotive force of the standard cell, and adjust the auxiliary resistance box until the galvanometer gives no deflection. Then throw the switch to connect the unknown electromotive force in the galvanometer circuit and again adjust the potentiometer arms until the galvanometer gives no deflection. The reading of the potentiometer then gives the value of the unknown electromotive force.

(*b*) To measure an electromotive force of 15 volts or less. Use an auxiliary battery of about 15 volts electromotive force, and proceed exactly as under (*a*) above, using only the hundreds', tens', units', and tenths' arms to indicate the successive digits in the number which expresses the known electromotive force of the standard cell, but using all of the potentiometer arms when the unknown electromotive force X is connected in the galvanometer circuit.

(*c*) To measure an electromotive force of 150 volts or less. Use an auxiliary battery of about 150 volts electromotive force,

and proceed exactly as under (*a*) above, using only the tens', units', and tenths' arms to indicate successive digits in the number which expresses the known electromotive force of the standard cell but using all of the potentiometer arms when the unknown electromotive force X is connected in the galvanometer circuit.

In measuring a high electromotive in this way the result is only reliable to three significant figures because of the fact that the value of the known electromotive force of the standard cell cannot be accurately represented by three digits. A more satisfactory procedure in the case of a large electromotive force is the following, which, indeed, can be used also for small electromotive forces.

(*d*) Connect the electromotive force to be measured through an accurately known resistance to the B posts of the potentiometer. Throw the switch so as to connect the standard cell into the galvanometer circuit, and adjust the potentiometer arms until the galvanometer gives no deflection. Then the ratio of the unknown electromotive force to the known electromotive force of the standard cell is equal to the ratio of the total resistance in the circuit (including the potentiometer and auxiliary resistance box) to the resistance between the points of contact of the arms A and A', Fig. 110*a*, which latter resistance is given directly by the reading of the potentiometer arms.

In working with the potentiometer it is necessary to connect the unknown electromotive force, the standard cell, and the battery B, each in the proper direction as indicated by the plus and minus signs marked on the potentiometer case, and the electromotive force of the battery B in Fig. 110*a* must exceed the electromotive force between the arms A and A'.

To show that these two conditions are satisfied, set all the potentiometer arms at zero and note the direction of the galvanometer deflection and then set all of the potentiometer arms at their maximum readings and again note the direction of the galvanometer deflection. If the second galvanometer deflection is opposite to the first, the connections are correct. If the direc-

tion of deflection has not been reversed, the auxiliary battery may be connected backwards, or the electromotive force of the auxiliary battery may be too small, or a broken circuit may exist.

The adjustment of the auxiliary resistance box to give zero deflection of the galvanometer when the potentiometer arms are set at a given reading does not involve unusual manipulations. In the adjustment of the potentiometer arms to give zero deflection of the galvanometer, proceed as follows:

1. Set all of the arms at zero and note the direction of the galvanometer deflection.

2. Swing the thousands' arm to its maximum reading and again note the direction of the galvanometer deflection. If the galvanometer deflection is opposite to that obtained under (1), the connections are correct.

3. Step the thousands' arm backward until the galvanometer deflects in its original direction (1).

4. Bring the hundreds' arm to 900. If the direction of the galvanometer deflection is then the same as under (1), this arm is in the correct position; if not, step it backward until the direction of the deflection becomes the same as under (1).

5. Adjust the other arms, tens, units and tenths, in succession, as described under (4).

Work to be done. — Standardize and calibrate a voltmeter. Connect the voltmeter terminals to the X terminals of the potentiometer, and also connect the voltmeter terminals through a resistance box to a battery of which the electromotive force is fairly constant. Adjust the resistance of the box to give a series of readings on the voltmeter, and in each case determine the true value of the electromotive force.

The battery which is used to supply current to the voltmeter as here specified must be separate from the battery B in Fig. 110*a*.

If method (*d*), as above described, is to be used for measuring the true value of the electromotive force corresponding to the various voltmeter readings, then the voltmeter terminals must be connected to the B terminals of the potentiometer by fairly short

thick wires, the B terminals of the potentiometer must be connected through a resistance box to a battery, this resistance box must be adjusted to give a series of voltmeter readings, and the true value of the electromotive force corresponding to each determined, as explained under (d) above.

Results. — Plot a curve of which the abscissas represent observed voltmeter readings and of which the corresponding ordinates represent the true values of the electromotive force across the voltmeter terminals as measured by the potentiometer.

The Leeds and Northrup potentiometer. — The potentiometer of Leeds and Northrup is arranged as shown in Fig. 111*a*, and a general view of the instrument is shown in Fig. 111*b*. The

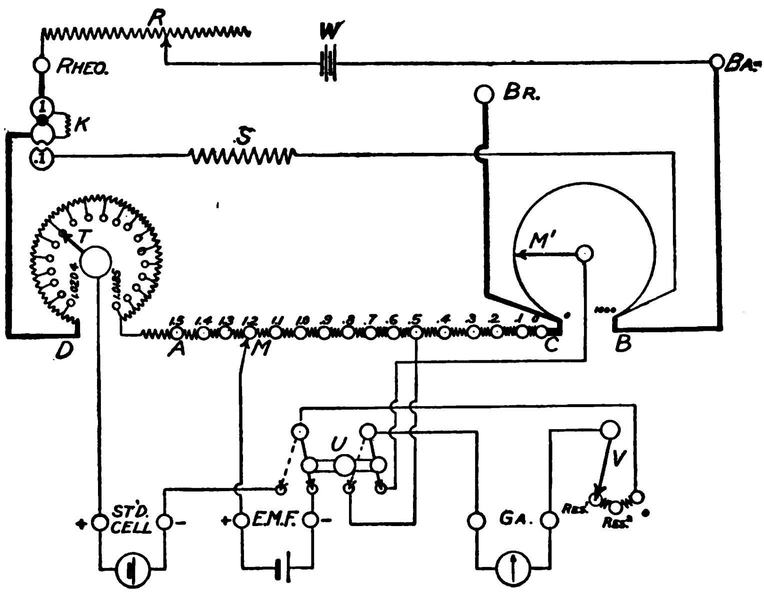

Fig. 111a.

auxiliary battery W produces current through the circuit $DAMCB$; AC is a series of fifteen 5-ohm coils; and CB is a 5-ohm slide-wire mounted as several turns of wire on a marble cylinder. The standard cell (cadmium standard) is connected from the point 0.5 to the switch T, the switch T is turned to

the point corresponding to the observed temperature of the standard cell (the contact points of the switch T are numbered to correspond to the observed temperatures of the cell), and the rheostat R is adjusted until the galvanometer, which is connected in circuit with the standard cell by throwing the switch U into the dotted position, gives no deflection. The current flowing through the potentiometer circuit is then exactly one fiftieth of an ampere. The switch U is then thrown to connect the unknown electromotive force (marked E.M.F. in the figure) through the galvanometer to the moving contact M and the sliding contact M'. The sliding contact M' is brought to the zero end of the slide-wire, the contact M is moved from C towards A, step

Fig. 111b.

by step, until the galvanometer deflection is reversed, and left on the last point for which the galvanometer deflection is the same as when M is at C, then the contact point M' is moved until the galvanometer gives no deflection. The reading of the contact point M gives the value of the electromotive force to a tenth of a volt, and the reading of the point M' gives hundredths, thousandths, and ten-thousandths of a volt directly, and by estimating a fraction of the smallest division, it gives hundred-thousandths of a volt.

The resistance S is one tenth the resistance of the potentiometer circuit. This resistance may be connected in parallel with the potentiometer circuit by moving the plug No. 1 to the point marked 0.1. The resistance K then makes the total resistance of the potentiometer the same as before, so that the total current is unchanged. Only one tenth of this current, however, flows through the potentiometer circuit, and under these conditions the potentiometer reads to tenths, hundredths, thousandths, ten-thousandths, and hundred-thousandths of a volt directly.

One advantage of this potentiometer is that there is no movable contact in the potentiometer circuit, and another advantage is the quickness with which the standard cell may be applied to check the value of the current through the potentiometer circuit. The post marked BR is intended to be used when it is desired to use the slide-wire CB as a Kohlrausch bridge.

EXPERIMENT 84.

Standardization and Calibration of an Ammeter.

The object of this experiment is to standardize and calibrate an ammeter by means of the potentiometer and a standard resistance.

Work to be done. — Connect the ammeter A, Fig. 109, through a standard resistance S and an adjustable resistance R, as shown. Connect the auxiliary binding posts of the standard resistance to the X terminals of the potentiometer (see Fig. 110*c*). Adjust the resistance R, Fig. 109, to give a series of ammeter readings, and for each ammeter reading determine the electromotive force across the standard resistance by means of the potentiometer. The method of using the potentiometer is described under Experiment 83.

Plot a curve of which the abscissas represent the ammeter readings and the ordinates represent the true values of current.

EXPERIMENT 85.

THE A.C.–D.C. COMPARATOR.

The object of this experiment is to standardize an alternating-current ammeter or voltmeter on the basis of a standard resistance and a standard cell.

Theory. — In direct-current ammeters and voltmeters, the force which acts upon the pointer and produces the deflection may be any function whatever of the current or electromotive force, provided only that the force has a perfectly definite value for a given current or electromotive force, thus ensuring that the given current or electromotive force will produce a definite deflection.

In a certain class of alternating-current ammeters and voltmeters, on the other hand, the force tending at any instant to move the pointer is proportional to the square of the current or electromotive force at that instant, so that the *average force*, upon which the steady deflection depends, is proportional to the *average square* of the electromotive force or current. Such instruments indicate effective values of alternating current and electromotive force correctly when they have been standardized and calibrated as direct-current instruments. Such instruments are therefore always standardized by the methods described in Experiments 81, 82, 83 and 84.

Other types of alternating-current ammeters and voltmeters, however, do not indicate effective values correctly when they have been calibrated as direct-current instruments. Such ammeters and voltmeters must be calibrated by alternating current or alternating electromotive force which for the purpose of the calibration is measured by independent means.

The A.C.–D.C. comparator is a device whereby the effective value of an alternating current or alternating electromotive force may be shown to be equal to the actual value of a direct current or direct electromotive force, so that the effective value of the alternating current or alternating electromotive force may be known when the direct current or direct electromotive force has

been accurately measured. This instrument depends upon the fact that an alternating current produces the same heating effect in a wire as a direct current when the effective value of the alternating current is equal to the actual value of the direct current.

Apparatus. — Figure 112 is a general view of the essential parts of the A.C.-D.C. comparator. Two very fine wires *AB* and *CD* (see Fig. 113*a*) are stretched between rigid supports and

Fig. 112.

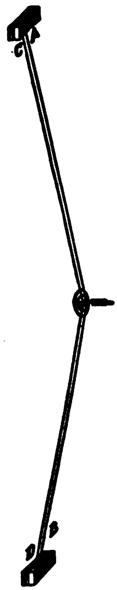

Fig. 113a.

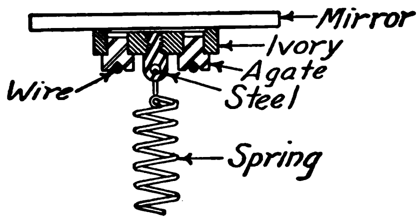

Fig. 113b.

pulled backwards by a light steel spring which engages a small cross-piece resting against the wires and carrying a mirror as shown in Fig. 113*b*. A telescope and scale are arranged to indicate deflections of the mirror due to the unequal sagging of the two wires. An alternating current flows through one of the wires *AB* and a direct current flows through the other wire *CD*, and when the telescope indicates no deflection of the mirror, the

direct current is equal to the effective value of the alternating current.*

Figure 114*a* shows the arrangement of the comparator for the standardization of an alternating-current ammeter *A*. The two wires of the comparator are represented by *ab* and *cd*, and *R* is a non-inductive resistance standard through which flows the alternating current to be measured.

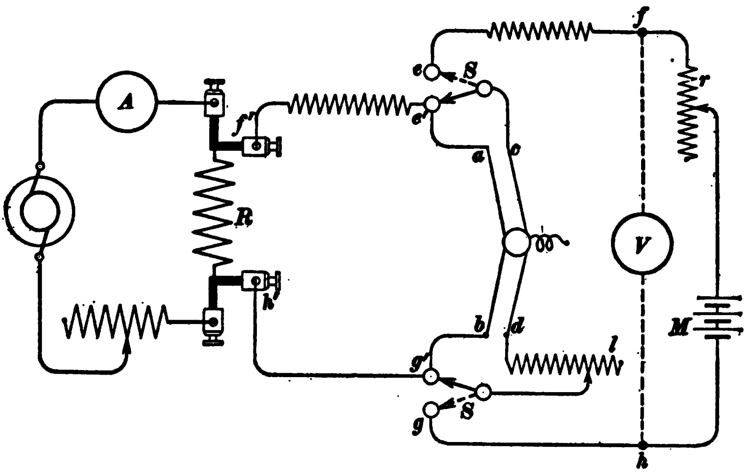

Fig. 114a.

Two switches *SS* are arranged so that the terminals of the wire *cd* may be connected either to *e'* and *g'* or to *e* and *g*, *r* is a regulating rheostat by means of which the battery *M* may produce any desired electromotive force between the points *f* and *h*, and *V* is an accurate direct-current voltmeter or potentiometer for measuring the voltage across *fh*.

To make a measurement, throw the switches *SS* so as to connect both comparator wires to the terminals of *R* (the desired positions of the switches *SS* are shown by the full lines in the figure), and then with the current that is to be measured flowing through *R*, adjust the rheostat *l*† until the comparator mirror

*The exact method of using the A.C.–D.C. comparator departs from this statement slightly, as will be seen later.

† CAUTION ! *Start with maximum resistance in l and r, and thus avoid burning out of comparator wires.*

shows no deflection. Now throw the switches SS so as to connect the comparator wire cd to the direct-current source (the correct positions of the switches SS are shown by the dotted lines), and regulate the rheostat r until there is again no deflection. Then the electromotive force E read by the instrument V is equal to the effective electromotive force across the terminals of the standard resistance. The resistances of the leads $e'f'$ and $g'h'$ must be the same as the resistances of the leads ef and gh. The effective value of the current flowing through the ammeter A is then equal to (E/R) plus the current which flows through the wire ab. The current which flows through the wire ab varies with the electromotive force E and it may be represented as a function of E, namely $[f(E)]$. The current through the ammeter therefore is equal to $(E/R)+f(E)$. The value of $f(E)$ is equal to E divided by the resistance of the wire ab, but this resistance varies slightly with the voltage on account of the considerable temperature changes of the wire. The value of $f(E)$ is therefore supplied by the maker of the comparator in the form of a plotted curve of which the abscissas represent the value of E and the ordinates the corresponding values of the current in the wire ab.

When the comparator is used for standardizing a voltmeter, the connections are as shown in Fig. 114*b* in which V' is the alternating voltmeter that is being standardized. In this case, large but equal resistances are inserted in both pairs of leads $e'f'-g'h'$, and $ef-gh$.

Work to be done. — Connect up an alternating-current ammeter A, a non-inductive standard resistance R, and the A.C.–D.C. comparator as shown in Fig. 114*a*, using either a standard direct-current voltmeter or a potentiometer for measuring the electromotive force across fh. Connect the ammeter and non-inductive resistance standard through a suitable controlling rheostat to a source of alternating current of the desired frequency, and standardize the ammeter for a series of readings ranging over its entire scale.

Using accurate direct-current ammeter and voltmeter observe a series of corresponding values of current $f(E)$ through the wire *ab* and of electromotive force E across the terminals of *ab*.

Results. — Plot a curve of which the abscissas represent the

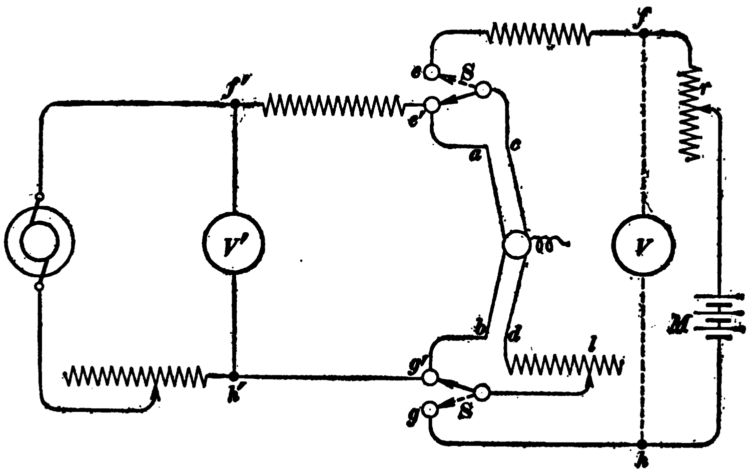

Fig. 114b.

values of E and of which the ordinates represent the values of $f(E)$.

Plot a curve of which the abscissas represent the readings of the alternating current ammeter and of which the ordinates represent the corresponding true effective values of alternating current.

EXPERIMENT 86.

Study of a Siemens Electrodynamometer.

The object of this experiment is to standardize a Siemens electrodynamometer and to study its errors.

Theory of the instrument. — The turning force with which the fixed coil acts upon the movable coil of an electrodynamometer is proportional to the square of the current flowing through the

instrument. In the Siemens electrodynamometer this turning force, or torque, is balanced by the twisting of a helical spring. The torque due to the spring is proportional to the angle ϕ through which the spring is twisted, so that ϕ is proportional to the square of the current i flowing through the instrument. That is,

$$\phi = ki^2 \tag{i}$$

or

$$i = m\sqrt{\phi} \tag{ii}$$

where k and m are constants. The constant m is called the reduction factor of the instrument. Equation (ii) is always used in reducing the readings of the Siemens electrodynamometer.

Effect of Earth's Magnetic Field upon the Siemens Electrodynamometer. — Let H be the horizontal intensity of the earth's magnetic field and θ the angle between H and the plane of the movable coil of the electrodynamometer. Then $H \cos \theta$ is the component of H in the plane of the coil, and this component of H acts upon the movable coil with a torque which is proportional to $i \times H \cos \theta$ or equal, say, to $k'iH \cos \theta$. The total torque acting upon the movable coil is therefore equal to $ki^2 + k'iH \cos \theta$, and this torque is balanced by an angle of twist ϕ' which is proportional to it. That is,

$$\phi' = ki^2 + k'iH \cos \theta \tag{iii}$$

in which k and k' are constants.

This equation (iii) shows that equation (ii) is not true except when θ is equal to 90°. Therefore in using the Siemens electrodynamometer it is always set up so that its movable coil is approximately at right angles to the earth's horizontal field H.

Elimination of the Effect of the Earth's Field by Reversals. — Let ϕ'' be the observed angle of twist of the helical spring when the current i, equation (iii), is reversed so as to become $-i$. Then equation (iii) becomes

$$\phi'' = ki^2 - k'iH \cos \theta \tag{iv}$$

From equations (iii) and (iv) we have

$$\phi' + \phi'' = 2ki^2$$

or

$$\frac{\phi' + \phi''}{2} = ki^2 \qquad \text{(v)}$$

This equation is similar to equation (i) and it shows that equation (ii) may be used without error arising from the effects of the earth's field if

$$\frac{\phi' + \phi''}{2}$$

is used instead of ϕ.

Work to be done. — (*a*) Set up the electrodynamometer in a position for which θ is approximately equal to 90°; observe ϕ' and ϕ'' corresponding to a known current i, as measured by a standard ammeter, and calculate the reduction factor of the instrument.

(*b*) Observe a series of values of

$$\phi\left(=\frac{\phi' + \phi''}{2}\right)$$

for different values of i, and plot a curve showing the relation between ϕ and i.

(*c*) Set the instrument so that the angle θ is approximately equal to zero, and observe ϕ' and ϕ'' for a given current so as to determine the magnitude of the effect of the earth's field.

Note. — The earth's field has no effect on an electrodynamometer which is used for measuring alternating current.

EXPERIMENT 87.

Standardization of a Wattmeter.

The object of this experiment is to standardize a wattmeter.

Apparatus. — The experiment as here described applies to the Weston Compensated Wattmeter.* The internal connections of

* See Franklin and Esty's *Elements of Electrical Engineering*, Vol. 1, page 204.

this instrument are shown in Fig. 115; S is the stationary current coil; A and B are its terminals; M is the movable coil; C is the compensating coil (which is wound alongside of the winding of S); R' is a resistance which takes the place of C in the following test.

In standardizing the wattmeter, a measured electromotive force E is connected to the terminals I and b, Fig. 115, and a measured current I from any convenient source is sent through the

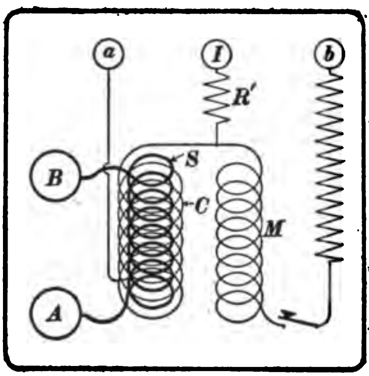

Fig. 115.

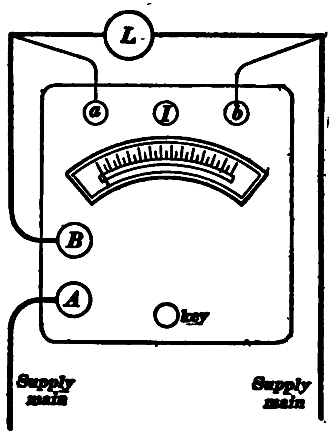

Fig. 116.

current coil S. The reading of the instrument is observed, and the corresponding true value of the indicated watts is equal to EI.

Caution. — In using a Weston compensated wattmeter, special care should be taken to avoid a large voltage between the compensating windings C and the current coil S, inasmuch as these two windings are very close together.

Figure 116 shows the connections of the wattmeter when it is used to measure the power delivered to a lamp L or other receiving circuit.

Work to be done. — Connect the lamp bank L to direct-current supply mains as indicated in Fig. 116. Arrange a standard voltmeter to measure the voltage across the points *ab* and arrange

a standard ammeter to measure the current delivered to the lamp bank.

Beginning with a single lamp connected in the lamp bank, take readings of voltmeter, ammeter, and wattmeter; and repeat ammeter, voltmeter and wattmeter readings for increasing numbers of lamps until the largest permissible current is reached.

If one lamp gives nearly full reading, a number of lamps may be connected in series to cut down the current.

Results. — From the readings taken, calculate the true watts corresponding to each wattmeter reading, and plot a curve of which the abscissas represent wattmeter readings and the ordinates represent the corresponding true watts.

EXPERIMENT 88.

Standardization of a Watt-hour Meter.

The object of this experiment is to standardize a watt-hour meter of the direct-current-motor type.*

Theory. — The speed of the watt-hour meter, that is, the rate at which the disk turns through angle, is proportional to the watts of power, that is, the rate at which work is delivered to the receiving circuit. Therefore, the total work delivered is proportional to the total angle or to the total number of revolutions turned by the disk, and the meter dials which record revolutions are divided so as to read watt-hours directly.

The errors of the instrument are:

(*a*) Those due to lack of exact proportionality between the rate at which work is delivered to the receiving circuit and the speed of the meter disk. On account of this error, the meter may record correctly for one value of power P, while the reading of the instrument may be in excess of the true work delivered when the power is greater than P, and less than the true work delivered when the power is less than P, or vice versa.

* See Franklin and Esty's *Elements of Electrical Engineering*, Vol. 1, page 204, for a description of the direct-current-motor type of watt-hour meter.

(*b*) The proportional relationship between power and speed may be accurate and the dial divisions may be such as to give readings always greater or always less than the true value of the work delivered.

There is no correction factor by which the reading of a watt-hour meter may be multiplied to give the exact value of work delivered to a customer in watt-hours. This is evident when we consider that the error in the recorded number of watt-hours varies with the value of the power delivered, so that 100 watts for 10 hours may produce a different record from that produced by 200 watts for 5 hours. It is, of course, possible to determine a correction factor by which the reading of a watt-hour meter may be multiplied to give a correct value of watt-hours when the meter has been operated at some definite load * and if the meter is properly constructed, this factor can be used for approximately correcting the reading of the meter in any case.

Work to be done. — The correction factor of the watt-hour meter is to be determined for a series of constant loads.

(*a*) Connect a lamp bank to direct-current supply mains through the watt-hour meter, arrange a standard voltmeter to measure the electromotive force across the supply mains and a standard ammeter to measure the current delivered to the lamp bank.

Caution. — There is usually a fixed connection in a watt-hour meter between the fine wire coil and the coarse wire coil, and if this connection is not duly considered in arranging the apparatus, a dangerous short-circuit may result.

(*b*) Observe the readings of the voltmeter and of the ammeter, and the speed of the disk of the watt-hour meter in revolutions per minute for a series of loads ranging from full load (all the lamps burning) to zero load.

(*c*) It is necessary to find the factor (which is essentially a gear ratio) by which the observed speed of the meter disk in revolutions per minute may be multiplied to give the speed of the

* The word "load" as here used means the power delivered to the receiving circuit.

meter in dial divisions per hour. This factor may be determined as follows: With full load (all the lamps burning) read the dials with the utmost precision at a given instant of which the clock reading is recorded. Let the meter run steadily for T hours (T equal to one half hour is usually sufficient) and then read the dials again and record the clock reading. During this run observe the speed of the meter disk repeatedly by counting the revolutions of the disk for periods of two or three minutes each. Let s be the mean speed of the disk in revolutions per minute and let W be the difference in the dial readings at the beginning and end of the run; this difference being, of course, expressed in "watt-hours." Then the factor by which any observed speed of the meter disk in revolutions per minute is to be multiplied to give the speed of the meter in dial divisions per hour ("watt-hours" per hour) is equal to $W/(Ts)$.

Computations and results. — (*a*) Calculate the speed of the meter in dial divisions per hour for each observed speed of the meter disk as obtained under (*b*) above, and plot a curve of which the values of EI (true watts) are the abscissas and the corresponding values of speed in dial divisions per hour are the ordinates.

(*b*) From the results of the above calculation, calculate the watt-hours which would be recorded by the watt-hour meter if it were operated five hours continuously at full load, half load, and quarter load, and find the ratio of true watt-hours to recorded watt-hours in each case.

EXPERIMENT 89.

COMPARISON OF RESISTANCE STANDARDS BY CAREY-FOSTER'S METHOD.*

Theory of the method. — Figure 117 shows the arrangement of a special type of Wheatstone's bridge designed by Carey-Foster for comparing two nearly equal resistances S_1 and X, and

* See *Philosophical Magazine*, May, 1884; Glazebrook and Shaw, "Practical Physics," 2d edition, p. 561; Glazebrook, *Philosophical Magazine*, October, 1900.

Fig. 118 shows the arrangement reduced to the conventional diagram of connections of a Wheatstone's bridge

S_1 is a resistance *standard* and X is a *copy* of the standard,

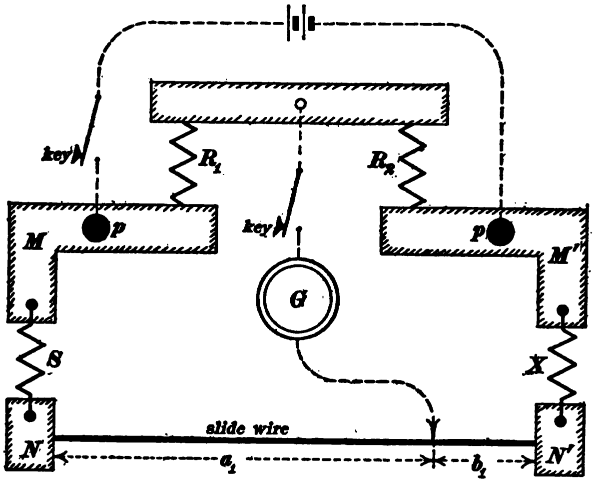

Fig. 117.

and the object in view is to compare X with S_1 and thus determine the exact value of X.

R_1 and R_2 are two nearly equal auxiliary resistances; M, N, N', and M' are the resistances of the copper connect-

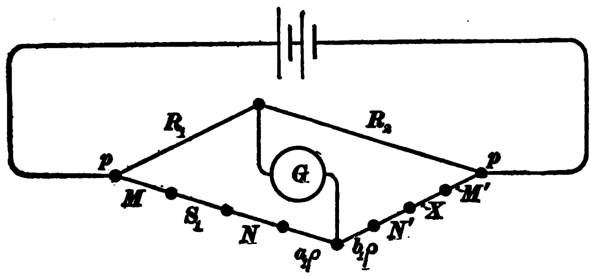

Fig. 118.

ing straps and joints, ρ is the resistance per unit length of the slide wire, and $a_1\rho$ and $b_1\rho$ are the resistances of the respective parts a_1 and b_1 of the slide wire.

(*a*) The slider is adjusted until the galvanometer gives no deflection, then:

$$\frac{R_2}{R_1}=\frac{X+M'+N'+b_1\rho}{S_1+M+N+a_1\rho} \tag{i}$$

(*b*) The positions of S_1 and X are interchanged and the slider is again adjusted until the galvanometer gives no deflection, then:

$$\frac{R_2}{R_1}=\frac{S_1+M'+N'+b_2\rho}{X+M+N+a_2\rho} \tag{ii}$$

in which a_2 and b_2 are the two segments of the slide wire in this second adjustment.

Adding unity to both members of equations (i) and (ii) and we have

$$\frac{R_1+R_2}{R_1}=\frac{X+M'+N'+b_1\rho+S_1+M+N+a_1\rho}{S_1+M+N+a_1\rho} \tag{iii}$$

and

$$\frac{R_1+R_2}{R_1}=\frac{S_1+M'+N'+b_2\rho+X+M+N+a_2\rho}{X+M+N+a_2\rho} \tag{iv}$$

Now $(a_1\rho+b_1\rho)$ is equal to $(a_2\rho+b_2\rho)$ since each is equal to the total resistance of the slide wire. Therefore the numerators of the right-hand members of equations (iii) and (iv) are equal, and therefore the denominators are equal also, so that:

$$S_1+M+N+a_1\rho=X+M+N+a_2\rho \tag{v}$$

or

$$S_1-X=(a_2-a_1)\rho \tag{vi}$$

The difference (a_2-a_1) is the length of slide wire included between the two positions of the slider for the two adjustments (*a*) and (*b*) above. Therefore equation (vi) gives the difference between S_1 and X in terms of the resistance of the observed length (a_2-a_1) of the slide wire.

Let another resistance standard S_2, slightly different in value from S_1, be substituted for S_1 in the bridge arrangement of

Fig. 117, and let the two adjustments (*a*) and (*b*) be again made; then:

$$S_2 - X = (a_4 - a_3)\rho \qquad \text{(vii)}$$

in which $(a_4 - a_3)$ is the length of the bridge wire between the two observed positions of the slides.

The values of both X and ρ may be calculated from equations (vi) and (vii), since S_1, S_2, $(a_2 - a_1)$, and $(a_4 - a_3)$ are known.

Practical form of the Carey-Foster bridge. — Figure 119 is a top view of a Carey-Foster bridge provided with two commutators, *abcd* and *ijkl*, for interchanging the standards S_1 and

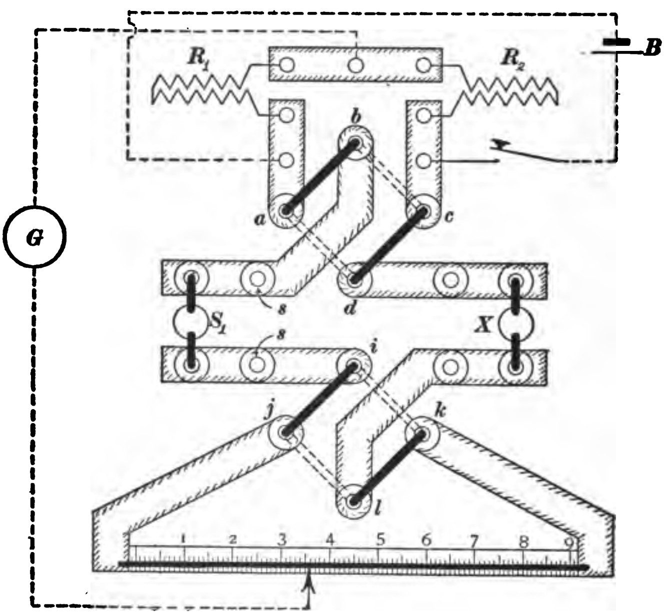

Fig. 119.

X without removing either S_1 or X from the oil-baths in which they are immersed. One arrangement of connections through the commutators is indicated by the heavy black lines *ab*, *cd*, *ij* and *kl*, and the other arrangement of connections which effects an

interchange of S_1 and X is indicated by the dotted lines *ad*, *bc*, *ik*, and *jl*.

The standards S_1 and X are immersed in oil-baths to keep them at uniform temperature and to make it possible to determine the temperatures of the standards by thermometers placed in the oil-baths. The standards are usually provided with a hole in the top of the containing case through which the bulb of a thermometer may be inserted into the interior of the coil of wire which constitutes the resistance element of the standard.

The standard S_2 is usually made by leaving S_1 in place *and connecting a higher resistance standard in parallel with* S_1 by placing the higher resistance standard in the same oil-bath with S_1 and with its terminals in the mercury cups *ss*. Thus if S_1 is a one-ohm standard (and of course X is a one-ohm coil of which the exact value is to be determined), then for S_2 one may use S_1 and a ten-ohm standard connected in parallel; in which case the value of S_2 will be $\frac{10}{11}$ ohm. If S_1 is a $\frac{1}{10}$-ohm standard (and of course X is a $\frac{1}{10}$-ohm coil of which the exact value is to be determined), then for S_2 one may use S_1 and a one-ohm standard connected in parallel; in which case the value of S_2 will be $\frac{1}{11}$ ohm. To avoid the necessity of lifting the standard which connects to the mercury cups *ss* out of the oil-bath it may be raised and supported on dry pine blocks placed across the cups *ss*.

The flat copper bottoms of the mercury cups, the flat ends of the copper terminals of the resistance standards, and flat ends of the copper commutator rods should be thoroughly amalgamated.

In placing the resistance standards and commutator rods in position always grind the flat ends of the copper rods back and forth over the bottoms of the mercury cups so as to remove any chance particle of dirt, and thus ensure perfect electrical contact.

The connections of the auxiliary resistances R_1 and R_2 must be thoroughly cleaned and tightly clamped. Variations of resistance of battery connections and of galvanometer connections do not introduce errors into the result.

To eliminate errors due to thermo-electromotive forces at the

contact points of different metals in the bridge apparatus, the battery should be connected to the points pp through a reversing switch and each adjustment of the slides should be made twice as follows: (1) With given battery connections and (2) with battery connections reversed.

Outline of observations. — Place S_1 and X in position, and also place the higher resistance standard which is to be connected later in parallel with S_1, in the oil-bath with S_1 with its terminals insulated from the mercury cups by small blocks of dry wood. Place a thermometer in the interior of each S_1 and X.

1. Observe and record temperatures of S_1 and X.

2. With commutators in "black" position and with battery "direct," observe a_1 twice, once when the slider is brought to the balance point from the right and once when the slider is brought to the balance point from the left. Record each observed value of a_1.

3. Reverse battery and again observe a_1 twice as in 2.

4. Repeat 2 and 3.

Note. — The mean of these eight observed values of a_1 is to be used for a_1 in equation (vi).

5. Change commutators to "dotted" position and repeat 2, 3 and 4. Record the eight observed values of a_2.

6. Observe and record temperatures of S_1 and X.

The higher resistance standard is now lowered into its mercury cups and the observations are continued as follows:

7. With commutators in "black" position and with battery "direct" observe a_3 twice as in 2.

8. Reverse battery and again observe a_3 twice as in 2.

9. Repeat 7 and 8 thus getting in all eight observed values of a_3.

10. Change commutators to "dotted" position, and repeat 7, 8, and 9. Record the eight observed values of a_4.

11. Observe and record temperatures of S_1 and X.

12. Record laboratory numbers of all standards used and of X.

Calculation of results. — From the certificates accompanying

S_1 and the higher resistance standard calculate the exact values of S_1 and S_2 at the mean temperature of S_1 which prevailed during the observations.

Then using equations (vi) and (vii) calculate the exact value of X (and also as a matter of interest the value of ρ), and in giving the result in your report specify the temperature at which the coil X has the value thus calculated.

CALIBRATION OF BRIDGE WIRE.

In the practice of Carey-Foster's method for the comparison of resistance standards it would be necessary only to standardize the bridge wire, that is, to measure the resistance of a known length of it, if the wire were perfectly uniform. However, the lack of uniformity in the resistance of the bridge wire usually introduces appreciable errors into the result, and for accurate work the wire must be calibrated.

The object of this calibration is to determine data from which a curve may be plotted, the abscissas of which represent readings on the slide wire scale, and the ordinates represent true resistances of the wire from any convenient starting point up to the reading.

The Carey-Foster method as outlined above may be used for this calibration. The calibration corrects not only for non-uniformity in the wire but for errors of the scale as well.

Procedure. — Choose two resistance standards S_1 and S_2 such that the difference $S_1 - S_2$ is equal to, say, 10 centimeters of the bridge wire. Put in place of R_1 and R_2, Fig. 119, two resistance boxes. Adjust the resistances in these boxes until the balance reading a_1 of the slide-wire scale is at the above-mentioned starting point. (The middle portion only of the bridge wire is likely to be used in Experiment 89, so that the starting point may be taken one quarter of the length of the wire from one end.) Exchange S_1 and S_2 and take the balance reading a_2.

Put S_1 and S_2 in first position. Readjust R_1 and R_2 until the balance reading b_1 is near a_2 and on the side of a_2 towards a_1. Exchange S_1 and S_2 and take the balance reading b_2.

Put S_1 and S_2 in the first position. Readjust R_1 and R_2 until the balance reading c_1 is near b_2 and on the side of b_2 towards b_1. Exchange S_1 and S_2 and take the balance reading c_2. And so on.

In this way we obtain accurately measured overlapping lengths of wire, of each of which the resistance is equal to $S_1 - S_2$. Lay off along the axis of abscissas the scale readings a_1, a_2, b_1, b_2, c_1, c_2, etc. Erect an ordinate at a_2 equal to $S_1 - S_2$. Draw a straight line from the point $[a_1, 0]$ to the point $[a_2, (S_1 - S_2)]$. Measure the height h from b_1 to this line, and erect at b_2 an ordinate equal to $h + S_1 - S_2$. Draw a line from the point $[a_1, (S_1 - S_2)]$ to the point $[b_2, (h + S_1 - S_2)]$. Measure the height h_1 from c_1 to this line. Erect an ordinate at c_2 equal to $h_1 + S_1 - S_2$. Draw a line from the point $[b_2, (h + S_1 - S_2)]$ to the point $[c_2, (h_1 + S_1 - S_2)]$ and so on. This broken line may then be inked as a smooth curve, and the difference in the ordinates of this curve at any two scale readings is equal to the resistance of the portion of the wire between the two readings.

EXPERIMENT 90.

Errors of a Resistance Box.

The object of this experiment is to determine the errors of the subdivisions of a resistance box.

Apparatus. — The errors of a resistance box are most easily determined by measuring each resistance in the box by means of a standard Wheatstone's bridge. The determination is to be made in the present instance, however, by grouping the subdivisions into approximately equal groups, and comparing them with each other. In this way a number of independent equations are obtained, one less than the number of subdivisions, and an additional equation is obtained by comparing one of the subdivisions with a standard. The true value of each subdivision may then be calculated.

The errors of the subdivisions are usually small and these errors may therefore be measured with sufficient accuracy in terms of the box resistances themselves.

The resistance box to be tested contains the following subdivisions: These subdivisions will hereafter be referred to by letter. The 1-, 2-, 3- and 4-ohm subdivisions will be treated as one subdivision together:

Nominal values.	Designating letter.
1, 2, 3, 4 ohms	*A*
10 ohms	*B*
20 "	*C*
30 "	*D*
40 "	*E*

It is especially important to see to it that there is no ambiguity as to the thing each letter stands for. Thus if there is more than one 1-ohm subdivision in the box it must be definitely stated which is included as a part of *A*. Furthermore, the box

which is being tested must be marked distinctly and a record made.

The box R to be tested and an auxiliary box X are connected to a special slide-wire bridge as shown in Fig. 120.

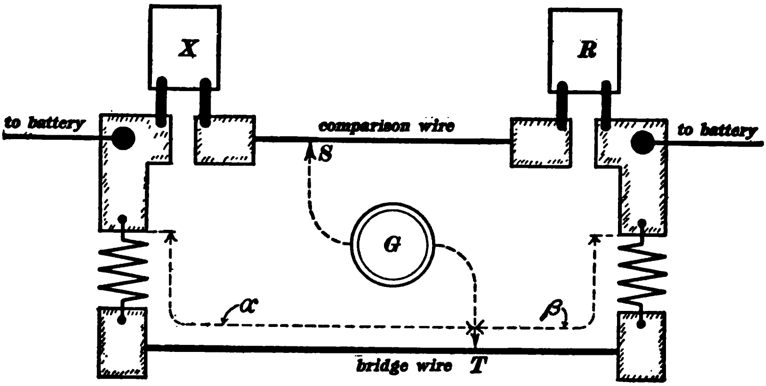

Fig. 120.

Before beginning the work the plugs of R and X should be carefully cleaned with a piece of cotton cloth. In the following directions no explanations are given. Full explanations must be included in the report.

Adjustment of Bridge Wire.

1. The slider S is moved to the middle of the comparison wire, and nominally equal resistances, say of 40 ohms, are put in R and X. The slider T is then adjusted until the galvanometer gives no deflection, and the position of the slider T is recorded.

2. The boxes R and X are interchanged (but not altered in any way), the slider T is again adjusted until the galvanometer gives no deflection, and the position T is again recorded.

3. The slider T is then moved to a position exactly midway between the two positions above determined and left in this position throughout the following work.

Operations 1, 2 and 3 have for their object the adjustment of the bridge arms α and β to exact equality.

STANDARDIZATION OF THE COMPARISON WIRE.

The errors of the subdivisions of box R are to be measured in terms of lengths of the comparison wire in Fig. 120, and reduced to ohms. For the purpose of this reduction to ohms the resistance per unit length of the comparison wire must be determined as follows:

4. Put one ohm in box R and zero ohms in box X, and adjust the slider S until the galvanometer gives no deflection, and record the reading of S.

5. Repeat with boxes R and X interchanged (but not otherwise altered).

The difference between these readings of S is the length of the comparison wire of which the resistance is one ohm. Explain this in your report and explain why the boxes may be taken to be correct so far as the standardization of the comparison wire is concerned.

PERFORMANCE OF TEST.

6. Balance the resistance A of the box R against a nominally equal resistance in box X, moving slider S, and record the reading of S.

Then balance the resistance B against identically the same resistance as before in box X, and record the reading of S. The difference between these two readings of S is half the difference between A and B. From this we have

$$B = A + a \tag{1}$$

in which a is the observed difference in ohms between A and B.

It is especially important to determine the sign of a; therefore all data having a bearing upon the sign of a must be recorded.

7. In an exactly similar manner determine the difference between $A + B$ and C, giving

$$C = A + B + b \tag{2}$$

Determine the sign of b and record conditions from which this sign is determined.

8. Similarly, find the difference between $B + C$ and D, giving

$$D = B + C + c \tag{3}$$

Determine the sign of c and record conditions determining its sign.

9. Similarly, find the difference between $B + D$ and E, giving

$$E = B + D + d \tag{4}$$

Record sign of d and record conditions which determine its sign.

We now have four independent equations (1), (2), (3) and (4), and five unknown quantities A, B, C, D and E. An additional independent equation may be obtained by comparing one of the subdivisions with a standard resistance. Let us, however, assume the equation:

$$A + B + C + D + E = 110 \text{ ohms} \tag{5}$$

This is equivalent to *defining* the ohm as $\frac{1}{110}$ of the combined resistance of A, B, C, D and E.

Solutions of equations (1) to (5). — Rewrite these equations,

$$B = A + a \tag{1}$$
$$C = A + B + b \tag{2}$$
$$D = B + C + c \tag{3}$$
$$E = B + D + d \tag{4}$$
$$110 \text{ ohms} = A + B + C + D + E \tag{5}$$

It is best to solve these equations algebraically, finding values of A, B, C, D and E in terms of a, b, c and d. The observed values of a, b, c and d may then be substituted in these final expressions. Outline of solution is as follows: Substitute the value of B from (1) in (2). Call the resulting equation (2′).

Substitute the values of B and C from (1) and (2′) in (3). Call the resulting equation (3′).

Substitute the values of B and D from (1) and (3′) in (4). Call the resulting equation (4′).

Substitute the values of B, C, D and E from (1), (2′), (3′), (4′) in (5), and solve for the value of A.

Substitute this value of A in (1), (2′), (3′) and (4′). We thus have the required expressions for A, B, C, D and E in terms of a, b, c and d.

EXPERIMENT 91.

Conductivity Test of Copper Wire.

The object of this experiment is to determine the conductivity and temperature coefficient of resistance of a sample of copper wire.

The British Institution of Electrical Engineers has proposed the following standards for commercial copper: *

1. Specific gravity of copper at 15.5° C. is 8.912 (555 lbs. per cubic foot).

2. Temperature coefficient of resistance of good commercial copper is 0.0043.

Annealed Copper Wire.

3. The commercial standard for annealed copper wire is 0.150822 international ohms at 15.5° C. for a wire 1 meter long weighing 1 gram. This corresponds to 10.20 ohms for a wire 1 foot long and 1 mil in diameter.

Hard Drawn Copper Wire.

4. Hard drawn copper wire is defined as that which will not elongate more than 1 per cent. without fracture.

5. The commercial standard for hard drawn copper wire is 0.153858 international ohms for a wire 1 meter long weighing 1 gram. This corresponds to 10.41 ohms for a wire 1 foot long and 1 mil in diameter.

* London *Electrician*, December 22, 1899.

Methods. — Two forms of Wheatstone's bridge are in use for measuring the very small resistances involved in the determination of the conductivity of a short sample of wire. One of these is an arrangement essentially similar to the Carey-Foster bridge which is shown in Fig. 119. The wire to be tested is used in place of the slide wire, and the performance of the test as outlined in Experiment 89 gives the length of the test wire of which the resistance is equal to the difference of the resistances of the two standards S_1 and X. A more convenient form of bridge for measuring low resistances is the Kelvin double bridge, the essential features of which are shown in Fig. 121, in which N is a standard resistance, and X is the resistance to be measured.

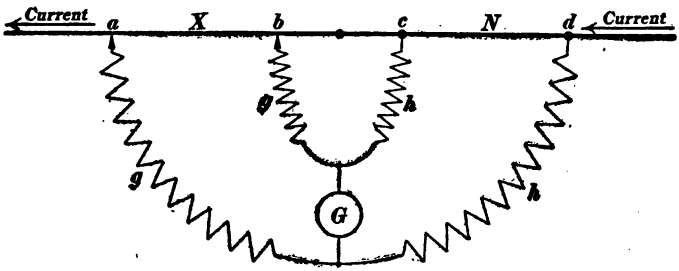

Fig. 121.

Usually the resistance X to be measured is the resistance of a portion of a wire between two knife-edge contacts a and b as shown in the figure. The two resistances N and X are connected as shown, and a current is sent through both in series. Auxiliary resistances gg and hh are connected, and the ratio g/h is adjusted until the galvanometer gives no deflection. Then the resistance of the portion ab of the wire under test is equal to g/h times the resistance of the standard. Figure 122 is a top view of the Reichsanstalt pattern of the Kelvin double bridge, that is to say, of the adjustable resistances gg and hh of Fig. 121. The terminals of the unknown resistance X, Fig. 121, are connected to the points XX, Fig. 122; the terminals of the standard N are connected to the points NN, Fig. 122; and

the galvanometer is connected to the posts G, Fig. 122. The two straight rows of resistances each containing 100, 50, and 25 ohms are the available values of hh (both must be the same in value), and the four dials give the value of the two resistances gg.

The resistance standard N should of course be submerged in an oil-bath, and the wire to be tested should also be submerged in an oil-bath so that its temperature may be controlled and accurately determined. The knife-edge contacts ab, Fig. 121, should be placed at an accurately measured distance apart.

Fig. 122.

Work to be done. — Place a sample of wire in the oil-bath and make the necessary connections as indicated in Figs. 121 and 122, using for N a suitable resistance standard, that is, a resistance standard such that the ratio X/N is as nearly equal to unity as may be. One usually has at one's disposal resistance standards of 0.001, 0.01, and 0.1 ohm, and that particular standard should be chosen which will give the value nearest unity for the ratio X/N.

Adjust the ratio g/h until the galvanometer gives no deflec-

tion and observe the temperatures of N and X. The oil-baths should be continuously stirred in order that the indicated temperatures may be the actual temperatures of N and X.

Heat the oil-bath which contains X to a temperature 20° or 30° C. above room temperature, keep it at an approximately constant temperature for some minutes, and then repeat the above determination.

Measure accurately the diameter of the wire and the distance between the knife edges *ab*, Fig. 121. Then carefully cut out and weigh the portion *ab* of the test wire.*

Computations and results. — From the above data, determine the specific resistance of the sample of wire at a specified temperature (resistance in ohms of a wire one centimeter long and one square centimeter section), the temperature coefficient of resistance of the sample of wire, the resistance of a wire one meter long and weighing one gram at a specified temperature, and the resistance of a wire one foot long and one mil in diameter at a specified temperature.

EXPERIMENT 92.

Temperature Coefficient of a Sample of Fine Wire.

The object of this experiment is to determine the resistance of a sample of fine wire at two specified temperatures, using a high-grade Wheatstone's bridge, and taking every precaution to secure accuracy.

Apparatus. — A high-grade Wheatstone's bridge is an expensive piece of apparatus and its accuracy and reliability depend upon the exercise of great care in handling it (see directions on page 6). A high-grade Wheatstone's bridge should always be kept covered when not in actual use. The hard rubber top must be kept clean and free from dust and the fingers must be kept

* If the test wire is quite uniform, its mass per unit length may be determined from the weight and length of the whole sample, thus preserving the sample for further use.

away from it as much as possible. The brass taper-plugs must never be touched with the fingers. Handle them only by the hard-rubber top. Before using the bridge, clean all of the plugs by means of a piece of linen or muslin, wipe out the sockets by means of a piece of clean muslin drawn over the end of a soft pine stick, and wipe off the hard rubber top thoroughly. Then place the plugs in position, using a moderate pressure combined with a twisting movement of the hand. Excessive pressure is likely to damage the bridge. The resistance of a plug contact may be made as small as 0.0001 if proper care is taken, and if the plugs

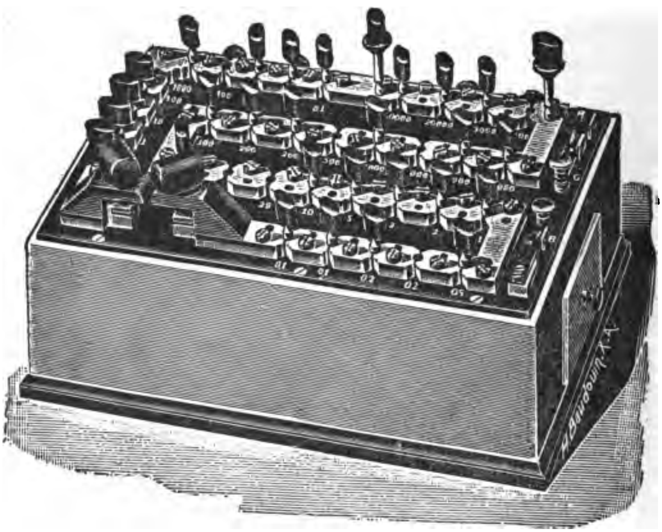

Fig. 123a.

are used improperly the resistance may be almost anything. *Proper handling and proper treatment of plugs is of fundamental importance in the accurate use of the Wheatstone's bridge.* Figure 123*a* shows a high-grade Wheatstone's bridge with plug connections, and Fig. 123*b* shows a high-grade Wheatstone's bridge in which the ratio arms have plug connections and the rheostat is arranged in decades with dial connections.

The sample of fine wire of which the resistance is to be meas-

ured may be wound in one layer upon a strip of window glass of which the corners have been well rounded with a file, and the ends of the wire should be soldered to heavy copper terminals which connect with massive binding posts at the top. When arranged in this way, the fine wire is in intimate contact with the oil of the bath, and its temperature may be accurately determined.

Work to be done. — Prepare a high-grade Wheatstone's bridge for use as explained above, and measure the resistance of the sample of wire at a series of observed temperatures increasing

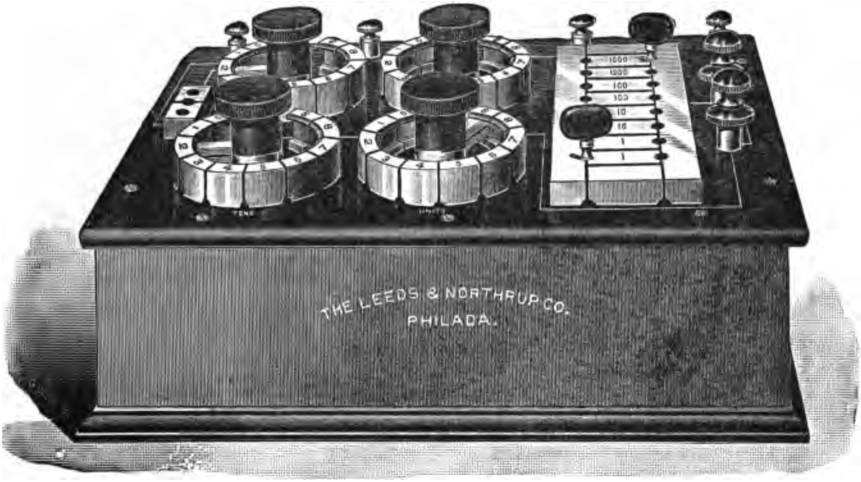

Fig. 1 3b.

very slowly from room temperature to 100° C. and then decreasing very slowly from 100° C. to room temperature. The temperature of the wire should be indicated by a very accurate thermometer, and the oil-bath should be continuously stirred.

Take every precaution to eliminate error in these determinations as briefly explained under Experiment 65.

Computations and results. — From the above data, plot a curve of which the abscissas represent temperatures and the ordinates represent the corresponding observed resistances of the sample of wire, and calculate the mean coefficient of the resistance of the sample of wire between room temperature and 100° C.

EXPERIMENT 93.

INSULATION TEST OF WIRE.*

The object of this experiment is to carry out the standard insulation test of a sample of wire.

Method. — The essential features of the method used in this test are described under Experiment 69. The test consists of two parts, namely, (*a*) the standardization of the sensitive galvanometer, and (*b*) the determination of the current produced through the insulation resistance by a known electromotive force. The reduction factor of a sensitive galvanometer is subject to very great changes and therefore the galvanometer must be standardized immediately before the second part of the test is performed.

Insulation tests can seldom be made with an accuracy greater than ten per cent. and, indeed, this degree of accuracy is sufficient for practical purposes inasmuch as the insulation of a sample of wire varies greatly with temperature and depends upon conditions which cannot be completely controlled. Therefore extreme accuracy need not be aimed at in standardizing the galvanometer and in taking the galvanometer deflections in the second part of the test.

Work to be done. — (*a*) Every preliminary arrangement having been made for the actual insulation test (*b*), standardize the galvanometer by the method explained in Experiment 69.

(*b*) Measure off about 200 feet of the insulated wire which is to be tested. Wind the wire in a coil small enough to go into the vat in which the wire is to be placed. In case of a large wire with thick insulation, the coil must be large in diameter so as to avoid any possibility of cracking the insulation by bending. Bend both ends of the wire at right angles to the plane of the coil as indicated in Fig. 124, and trim the ends of the insulation with a clean sharp knife very much as a pencil is sharpened.† This

* The details of this experiment are adapted from the *Physical Laboratory Notes* of the Massachusetts Institute of Technology, Eighth Edition, 1896.

† This tapering at the end of the insulation is unnecessary if a guard wire is used as explained in Experiment 69.

trimming is to secure a clean insulating surface over which the current cannot leak sensibly, and this surface must be kept perfectly clean during the test; it must not be touched with the fingers either during or after the trimming process.

2. The coil of wire so prepared is placed in the vat (empty). Prepare a sufficient quantity of slightly salted water to cover the coil of wire in the vat, and bring this water to a temperature of 75° F. by stirring into it a small quantity of hot water.

3. At a noted clock reading, pour this water into the vat so as to cover the coil, and connect the terminals of the galva-

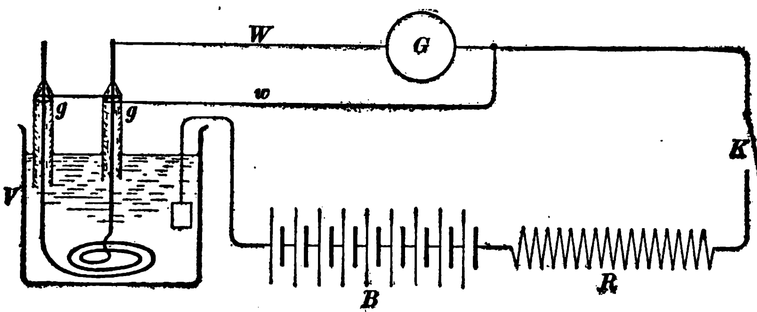

Fig. 124.

nometer to the wire and to a copper plate submerged in the vat *without any battery whatever being in circuit.* Under these conditions the galvanometer deflection should be zero, even when the galvanometer shunt is open, unless the coil has been in some way previously charged, or unless the insulation is perforated so that the water penetrates to the core and produces battery action. If the galvanometer should give a deflection, and if this deflection should not entirely disappear after five or ten minutes, or if the deflection is large and irregular, it is probable that the insulation is perforated, in which case it is useless to proceed with the test. This test (3) is called the *coil-discharge test* and it should never be omitted.

4. After the coil-discharge test is finished, the connections are changed to correspond with Fig. 124. It is specially important to connect the battery so that the current may flow from the water

through the insulation to the core of the insulated wire. Before closing the key *K*, the galvanometer shunt should be closed. Then record the temperature of the water, and if necessary bring it to within a few tenths of a degree of 75° F. Ten minutes after the original immersion of the coil of wire, close the key *K* permanently, and begin at once to observe the galvanometer deflections increasing the galvanometer shunt-resistance if necessary so as to obtain a readable deflection. Observe the galvanometer deflections every minute for fifteen minutes (it may be impossible to read the deflection of the galvanometer at first owing to the very large momentary current which flows into the insulated wire and charges it as a condenser). The zero reading of the galvanometer should be taken occasionally during this series of observations by opening the galvanometer circuit.

The galvanometer deflection usually continues to decrease for a long time after the battery is connected. In practice it is not desirable to wait for the deflection to become constant, and it is usual to take the deflection five minutes after the connection of the battery (fifteen minutes after immersion of the coil) as a basis for the calculation of the insulation resistance of the sample of wire. The other galvanometer deflections are important as indicating the general behavior of the coil.

5. After 25 minutes of immersion, connect the battery (close the key *K*), and at 30 minutes after immersion observe the galvanometer deflection. This deflection serves to determine the insulation resistance of the wire after 30 minutes of immersion. In the same way, determine the insulation resistance of the wire after 1, 3, 8 and 24 hours immersion. If the coil shows an exceedingly poor insulation after 15 minutes immersion, it is useless to prolong the test. If the insulation is so high tha tthere is no perceptible deflection of the galvanometer then the insulation resistance is beyond the range of the apparatus. In this case, the resistance corresponding to the least observable deflection should be calculated and stated as an insulation resistance above which the insulation of the wire is known to be.

EXPERIMENT 94.

Specific Resistance of Electrolytes.

The object of this experiment is to determine the specific resistance of a salt or acid solution, and to calculate the degree of dissociation of the salt or acid.

Apparatus. — In the measurement of the resistance of an electrolytic cell by means of the Wheatstone's bridge using direct current, large errors are produced by the polarization of the cell. These errors may be to a great extent avoided by using alternating current instead of direct current. In this case a telephone is used instead of a sensitive galvanometer, and the bridge arms are adjusted until the telephone gives no sound, or until the sound in the telephone is a minimum.

When alternating current is not available, a small induction coil is generally used; or, indeed, a plain inductance is used as

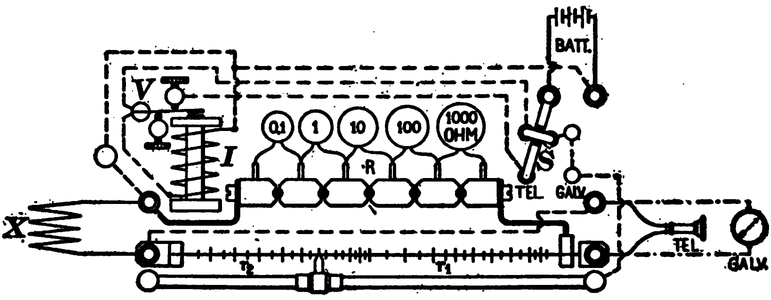

Fig. 125.

indicated in Fig. 125, which shows the details of the Kohlrausch slide-wire bridge. By tracing the connections it will be seen that the coil of wire *I* is in parallel with the bridge at the moment of contact of the vibrator *V*, so that the battery current flows through the bridge and through *I* in parallel. At the moment of break, on the other hand, the current continues to flow through *I* on account of its inductance, and therefore, since *I* is in parallel with the bridge, a reversed current flows through the

bridge. Thus an alternating current is produced. The switch S is arranged to properly connect the battery to the inductance coil I when the telephone is to be used, or to properly connect the battery directly to the bridge when the galvanometer is to be used.

In order to determine the specific resistance of an electrolyte from the measured resistance of an electrolytic cell a complicated calculation based upon shape and size of the cell would have to be made. It is much easier in practice to measure the resistance of the cell when filled with an electrolyte of which the specific resistance is known, and then measure the resistance of the cell when filled with the given electrolyte. Then

$$s = \frac{r}{R} S \tag{i}$$

where S is the specific resistance of the standard electrolyte, R is the resistance of the electrolytic cell when filled with the standard electrolyte, s is the specific resistance of the given electrolyte, and r is the resistance of the electrolytic cell when filled with the given electrolyte.

The standard electrolytic solutions ordinarily used are as follows:

Sulphuric acid of 30.4 per cent. H_2SO_4 by weight, specific gravity 1.224. The value of S for this solution at $t°$ C. is given by the equation

$$S = 1.36[1 - 0.0163(t - 18)] \tag{i}$$

Sodium chloride solution of 26.4 per cent. NaCl by weight, specific gravity 1.201. The value of S for this solution at $t°$ C. is given by the equation

$$S = 4.66[1 - 0.022(t - 18)] \tag{ii}$$

Magnesium sulphate solution of 17.3 per cent. $MgSO_4$ by weight, specific gravity 1.187. The value of S for this solution at $t°$ C. is given by the equation

$$S = 20.45[1 - 0.026(t - 18)] \tag{iii}$$

These values of S are the resistances of centimeter cubes in international ohms.*

The electrolytic cells to be used are shown in Fig. 126, a large, a medium, and a small-throated vessel being provided for each pair of electrodes. The electrodes are platinum disks covered

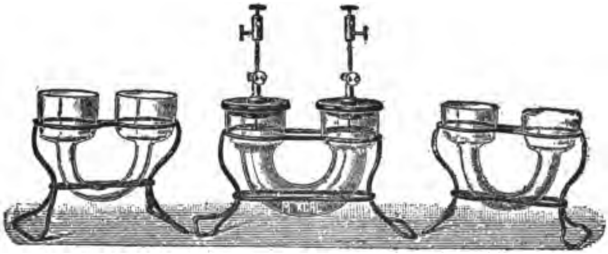

Fig. 126.

with a thin layer of spongy platinum so as to reduce polarization as much as possible.

Work to be done. — (*a*) Standardize each of the electrolytic cells by measuring its resistance when filled with a standard solution. The low-resistance sulphuric acid is best suited for standardizing the vessel with a narrow throat, and the higher-resistance solution of sodium chloride or of magnesium sulphate is better suited for standardizing the vessel with the wide throat. It is necessary to observe the temperature of the electrolyte very carefully.

(*b*) Take an accurately weighed amount of the standard sodium chloride solution, say 100 grams, and dilute it by adding 100 grams of distilled water and measure its specific resistance. Then add 200 grams of distilled water and again determine the specific resistance of the solution. Then add 400 grams of distilled water and again determine the specific resistance of the solution, and so on until the specific resistance becomes as large as can be conveniently measured with the given apparatus. In each case observe the temperature of the solution with great care, and if possible bring the temperature in each case to a prescribed value.

* See Kohlrausch, *Praktische Physik*, page 414, Leipzig, 1901.

Computations and results. — (*a*) Plot a curve of which the abscissas represent the strengths of the successive salt solutions in gram molecules per liter, and of which the ordinates represent the observed specific resistances. A gram molecule of a salt is equal to m grams of the salt, where m is the molecular weight of the salt. The volume of the salt solution in liters is approximately equal to $W/1{,}000$, where W is the weight of the solution in grams. This is quite accurate for dilute solutions.

(*b*) Calculate the ratio of dissociation of the salt solution at each concentration, and plot a curve of which the abscissas represent concentrations in gram molecules per liter and the ordinates represent degrees of dissociation in per cent.

The degree of dissociation is calculated as follows: Let c be the concentration of a salt solution in gram molecules per liter. The number of actual molecules of the salt per cubic centimeter is proportional to c and it may be taken equal to c for convenience.

In a solution of a given salt or acid of given concentration c and at a given temperature a definite fractional part p of the molecules of the salt or acid are dissociated into ions. The fraction p is called the *ratio of the dissociation* of the given salt or acid under the given conditions.

The ratio of dissociation always approaches unity with decreasing concentration, that is, all or nearly all of the molecules of any salt or acid are dissociated in very dilute solution.

The only molecules which take part in the conducting of the electric current through an electrolyte are those which are dissociated. That is to say, the number of molecules per cubic centimeter which take part in the conduction is equal to pc and the specific conductivity of the electrolyte (reciprocal of specific resistance, $1/s$) is proportional to pc. Therefore the specific conductivity of the electrolyte divided by pc is a constant. The value of this constant may be determined as follows: Consider a very dilute solution of which the concentration c' is known and of which the specific conductivity $1/s'$ has been determined. The

value of p for this solution is equal to unity, and therefore the value of the above-mentioned constant is equal to $1/s'$ divided by c'.

The value of the above-mentioned constant being thus determined, the degree of dissociation p corresponding to any concentration c can be calculated from the relation: $1/s$ divided by pc equals the above-mentioned constant, the specific resistance s of the solution having been determined.

EXPERIMENT 95.

Primary Battery Tests.

The object of this experiment is to familiarize the student with some of the more important commercial tests of a primary battery.*

What a systematic battery test includes.—(*a*) The most obvious quantities to be measured are electromotive force and internal resistance. High electromotive force means correspondingly high energy output for given zinc consumption, but of course with the added expense for depolarizing material such as chromic acid, manganese dioxide, and the like. High internal resistance is not particularly objectionable when the cell is used on a high resistance circuit, but a cell for the production of large current must have low internal resistance.

(*b*) It is desirable to know the manner in which the cell polarizes when it delivers current steadily to a receiving circuit of known resistance.

(*c*) It is also desirable to know the manner in which the cell recovers from polarization when it is left on open circuit after having been used.

(*d*) It is important to know, in the case of open-circuit cells, the amount of deterioration and local action that takes place when the cell is left standing for a long time on open circuit.

* See *Primary Batteries*, by H. S. Carhart, Boston, 1891, pages 115 to 156.

Thus, the ordinary dry cell deteriorates quite rapidly when not in use, unless the zinc and the ammonium chloride are very pure.

(*e*) It is desirable to know the approximate amount of service (total output of energy) that a cell can give. This cannot be easily determined on account of the long duration of the test required, and no test in this particular is so satisfactory as the test of actual service.

Methods of making tests. — 1. To measure the electromotive force of a voltaic cell use a low-reading voltmeter.

2. The simplest and perhaps the most important test of the resistance of a voltaic cell is to observe its short-circuit current. For example, the best test of a dry cell is to short-circuit it through an ammeter for a moment and observe the current produced. If the cell is exhausted or if it is dried out it gives only a small current on short circuit. Perhaps the most satisfactory method for measuring the resistance of a voltaic cell is Beetz's method as described below. The difficulty encountered in the carrying out of this method is due almost wholly to the fact that the resistance of a voltaic cell is indeterminate. More elaborate methods for measuring the resistance of a voltaic cell are no more reliable than Beetz's method.

3. To study the polarization of a voltaic cell, connect a low reading voltmeter to the cell, allow the cell to deliver current through a known resistance, and observe the reading of the voltmeter at intervals. The results of this test should be shown by a curve of which the abscissas represent elapsed time and the ordinates represent observed values of electromotive force.

The test that is nearly always employed for storage batteries is to measure the electromotive force of each cell by means of a low-reading voltmeter, an unusually low voltage indicates that a cell is not in good condition.

4. To study the recovery of a voltaic cell from polarization, break the circuit after test 3 and observe the electromotive force at intervals. The voltmeter should be disconnected between observations. The results of this test should be represented by a curve.

BEETZ'S METHOD FOR MEASURING THE RESISTANCE OF A VOLTAIC CELL.

A bare german silver wire WW, Fig. 127, is stretched on a board. At one end, this wire is soldered to a copper strap which dips into a mercury cup. E is the voltaic cell of which the re-

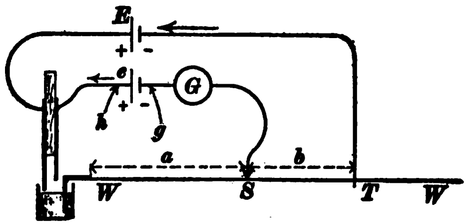

Fig. 127.

sistance is to be measured, e is an auxiliary cell the electromotive force of which is considerably less than the electromotive force of the cell E, and G is a sensitive galvanometer.

Connections are made with the mercury cup by dipping into it a stick to the sides of which are fastened two copper straps which project beyond the end of the stick, the projecting length of one strap being greater than that of the other, so that the cell E may be always connected before the cell e.

S is a sliding contact of which the resistance need not be considered, and at T the connecting wire is scraped, laid straight across WW and clamped so as to make a contact of negligible resistance.

The slider S is moved until the galvanometer gives no deflection when the stick is thrust momentarily into the mercury cup. Then we have

$$e = \frac{a}{R + a + b} \cdot E \qquad (1)$$

in which e and E represent the electromotive forces of the respective cells, R is the resistance of cell E together with its connecting wires, and a and b are the resistances of the portions of the german silver wire as indicated in Fig. 127.

The contact at T is now moved considerably nearer to the mercury cup and the slider S is again adjusted until the galvanometer gives no deflection. Then we have

$$e = \frac{a'}{R + a' + b'} \cdot E \tag{ii}$$

in which a' and b' are the new values of a and b.

From the equations (i) and (ii) the ratio e/E may be eliminated and the value of R calculated in terms of a, b, a' and b'.

The values of a and b are observed as lengths of wire and they are to be reduced to ohms, the resistance of unit length of the german silver wire being given (see instructor).

When E is a storage cell or other cell of high electromotive force e may be a gravity cell. When E is a cell of small electromotive force, then a sufficiently small auxiliary electromotive force may be obtained by soldering the connecting wires g and h, Fig. 127, to two points, six inches or so apart, on a fine wire a foot or so long which is connected to the terminals of an auxiliary gravity cell.

Work to be done. — Determine the resistance of a gravity cell, of a dry cell, and of a storage cell. Perform tests (1), (2), (3), and (4) upon the gravity cell and dry cell.

EXPERIMENT 96.

MAGNETIC TEST OF IRON. EWING'S METHOD.

The object of this experiment is to determine the relation between flux density and magnetizing force for a sample of iron.

Theory of the method. — A long slim rod, AB, Fig. 128, of the iron to be tested is placed in a vertical position in a long vertical coil of wire. The upper end A of the rod is on a level with, and at a distance d due magnetic east of a small suspended magnet at M. Let l be the length and q the sectional area of the iron rod. Let z be the number of turns of wire per centimeter length of the long coil, and let H be the

intensity of the horizontal component of the earth's magnetic field at M.

A measured current of i abamperes is sent through the magnetizing coil and the intensity of the magnetizing field is

$$\mathcal{H} = 4\pi z i \qquad (1)$$

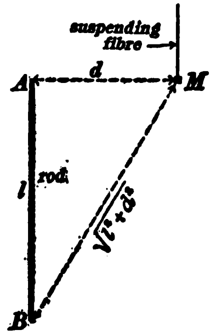

Fig. 128.

It remains to find the flux density $\mathcal{B}$ produced in the rod by this magnetizing field. Let m be the strength of the pole A, and $-m$ the strength of the pole B of the magnetized rod. These poles deflect the suspended magnet M through the angle ϕ, and the flux density in the rod is determined from this observed deflection as follows:

The horizontal field at M due to the pole A is $\frac{m}{d^2}$, and the horizontal component of the field at M due to the pole B is $-\frac{m}{l^2+d^2} \times \frac{d}{\sqrt{l^2+d^2}}$. Therefore the total horizontal field at M due to the magnetized rod is

$$h = \frac{m}{d^2} - \frac{md}{(l^2+d^2)^{\frac{3}{2}}} \qquad (2)$$

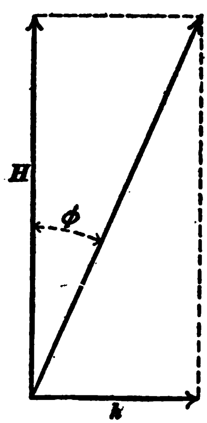

Fig. 129.

This field h is at right angles to the earth's horizontal field H, the suspended magnet turns through the angle ϕ and points in the direction of the resultant field, and from Fig. 129 we have

$$h = H \tan \phi \qquad (3)$$

Substituting this value of h in equation (2), we have

$$H \tan \phi = \frac{m}{d^2} - \frac{md}{(l^2+d^2)^{\frac{3}{2}}} \qquad (4)$$

This equation gives m when ϕ, d and l are observed and H

known. From the value of m thus obtained $\mathfrak{I}$ becomes known from the equation $\mathfrak{I}=\frac{m}{q}$, and $\mathfrak{B}$ becomes known from the equation $\mathfrak{B}=4\pi\mathfrak{I}+\mathfrak{H}$.*

A complete test of a sample of iron consists of the determination of a whole series of values of $\mathfrak{B}$ and $\mathfrak{H}$ in this way.

The most troublesome errors in this method are as follows:

1. The magnetizing field $\mathfrak{H}$ is somewhat less than $4\pi zi$ because of the demagnetizing action of the rod upon itself. This error is small when the rod is very long in comparison with its diameter.

2. The current in the magnetizing coil acts directly upon the suspended magnet and produces some deflection, whereas equation (4) assumes that the deflection is due entirely to the field which emanates from the magnet poles of the rod. This error is easily allowed for by using a compensating coil.

3. The poles A and B are not concentrated but they are spread over considerable portions of the ends of the rod. This source of error is in part provided against by placing the end A of the rod slightly higher in level than the suspended magnet M, and by taking l in equation (4) rather less than the actual length of the rod.

Practical Arrangement of Apparatus, Adjustments and Performance of Test.

1. A mirror is attached to the suspended magnet M, Fig. 128, and deflections are observed by means of a telescope and scale. The suspended magnet M is controlled by a governing magnet by means of which the directing field H can be changed until it is at right angles to the line d, Fig. 128. To make this adjustment, remove the test-piece to a distance of ten meters or more, and move the governing magnet until the telescope reading is in the middle of the scale, then fasten the governing magnet with wax.

* See Franklin & Esty, *Elements of Electrical Engineering*, Vol. 1, pages 356–366.

2. The magnet M is at the center of a circular coil of wire forming a tangent galvanometer. To determine the value of H, send a measured current i' through this coil and observe the scale reading in the telescope. Reverse the current and read again. Take half of the difference δ between these two readings, correct it by means of the table given on page 156, and let δ' be the corrected value of δ. Then $k\delta'$ may be used for the tangent of the angle of deflection, where k is a constant. So that from the equation of the tangent galvanometer we have

$$k\delta' = \frac{2\pi n i'}{\rho H} \tag{5}$$

in which n is the number of turns of wire in the circular coil and ρ is its radius.

3. The test-piece is surrounded by two solenoid coils. One is the magnetizing coil and the other is connected to an auxiliary battery and is used to neutralize the vertical component V of the earth's field. A resistance box in circuit with this coil is adjusted until the current is of the proper value to neutralize V. To make this adjustment read the zero point of the telescope and scale when the test-piece is at a distance of ten meters or more. Put the test-piece in place. Connect the secondary of a special transformer to the magnetizing coil, reduce the alternating current thus produced slowly to zero, and adjust the resistance in circuit with the neutralizing coil until the telescope reading comes to the zero point. Several trials will be necessary. This neutralizing coil and its connections are to be left undisturbed during the remainder of the test.

4. A compensating coil is connected in circuit with the magnetizing coil, and is adjusted until it neutralizes the direct action of the magnetizing coil upon the suspended magnet. To make this adjustment connect the magnetizing coil and this compensating coil in series to a battery and move the compensating coil until no deflection is produced when the circuit is closed.

Then clamp the compensating coil and leave its connections with the magnetizing coil untouched.

5. Everything is now in readiness for the test. Connect the battery which is to supply the magnetizing current, an ammeter *A*, a reversing switch *S*, a special rheostat, and the compensating and magnetizing coils as shown in Fig. 130. The special rheostat is constructed so that the magnetizing current can be re-

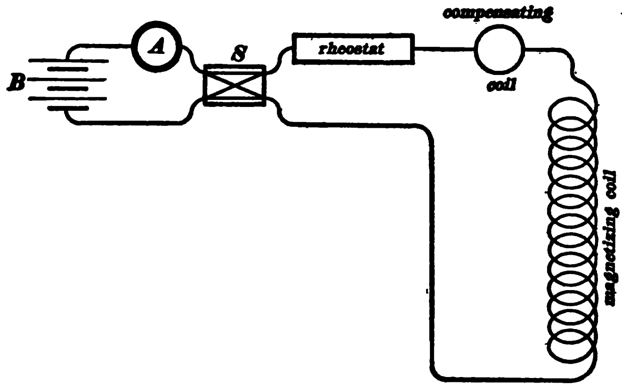

Fig. 130.

duced through five or six steps from its maximum value of, say, 1.5 amperes to, say, 0.1 ampere.

The reversing switch has two positions which will be designated by *A* and *B*.

5*a*. Starting with the maximum value of the magnetizing current reverse the current several times, leaving the switch finally in the *A* position, and observe the ammeter and the telescope and scale.

Reduce the magnetizing current one step, and again observe the ammeter and the telescope and scale, and so on until the smallest current is reached.

Then reduce the magnetizing current to zero and observe the telescope and scale.

Adjust the rheostat to give the smallest current (circuit open), set the switch in the *B* position, close the circuit, and read the ammeter and the telescope and scale.

Increase the magnetizing current one step and again read ammeter and the telescope and scale, and so on until the maximum magnetizing current is reached.

5*b*. Repeat the whole series of observations 5*a*, beginning with maximum magnetizing current with the B position of the reversing switch reducing step by step to zero, changing to the A position of the switch, and increasing by steps to the maximum magnetizing current.

6. Measure sectional area and length of test-piece, distance d, Fig. 128, and the distance D from the suspended magnet to the scale of the telescope.

Arrange these observations in a table like the one shown herewith. A sample set of current values is entered in the table to show about what the current steps should be. From each mean current and half difference of scale readings a pair of values of $\mathcal{B}$ and $\mathcal{H}$ is calculated.

The value of $\mathcal{H}$ is given at once by equation (1). The formula for $\mathcal{B}$ is derived as follows:

Correct the half difference Δ of scale readings by means of

TABULAR ARRANGEMENT OF OBSERVATIONS.

Series 5*a*.			Series 5*b*.			Mean Current.	Half Difference Δ of Scale Readings.	Corrected Half Difference Δ'.	$\mathcal{H}$	$\mathcal{B}$
Step.	Current.	Scale Reading.	Step.	Current.	Scale Reading.					
1A	1.489		1B	1.491		1.490				
2A	0.742		2B	0.742		0.742				
3A	0.366		3B	0.367		0.3675				
4A	0.173		4B	0.175		0.174				
5A	0.087		5B	0.086		0.0865				
	0.000			0.000		0.000				
5B	0.087		5A	0.087		o 087				
4B	0.174		4A	0.176		0.175				
3B	0.365		3A	0.368		0.3665				
2B	0.744		2A	0.746		0.745				
1B	1.486		1A	1.488		1.487				

the table given on page 156 so that $k\Delta'$ may be used for tan ϕ in equation (4) giving

$$Hk\Delta' = m\left(\frac{1}{d^2} - \frac{d}{(l^2 + d^2)^{\frac{3}{2}}}\right) \qquad (6)$$

Substitute the value of H from equation (5) and we have

$$\frac{2\pi n i' \Delta'}{\rho\delta'} = m\left(\frac{1}{d^2} - \frac{d}{(l^2 + d^2)^{\frac{3}{2}}}\right) \tag{7}$$

Substituting the value of m from this equation in the equation $\mathfrak{J} = \frac{m}{q}$, and substituting the value of $\mathfrak{J}$ from this equation and the value of $\mathcal{H}$ from equation (1) in the equation $\mathcal{B} = 4\pi\mathfrak{J} + \mathcal{H}$, we have

$$\mathcal{B} = \text{constant} \times \Delta' + 4\pi z i \tag{8}$$

in which

$$\text{constant} = \frac{8\pi^2 n i'}{\rho q \delta'\left(\frac{1}{d^2} - \frac{d}{(l^2 + d^2)^{\frac{3}{2}}}\right)}$$

Plotting of curve of $\mathcal{B}$ and $\mathcal{H}$, and determination of hysteresis loss. — Plot each value of $\mathcal{B}$ for both + and − values of $\mathcal{H}$ corresponding to it. Determine the enclosed area and multiply this area by $ab/4\pi$, where a is the number of units $\mathcal{H}$ represented by unit abscissa and b is the number of units $\mathcal{B}$ represented by unit ordinate. This gives the work lost per cubic centimeter per cycle for the given range of $\mathcal{B}$. From this result calculate the value of the constant n' in Steinmetz's equation,

$$\text{energy loss per c.c.} = n'\mathcal{B}^{1.6}$$

EXPERIMENT 97.

MAGNETIC TEST OF IRON. ROLAND'S METHOD.

The object of this experiment is to determine the relation between flux density and magnetizing force for a sample of iron.

Theory of the method. — A ring of the iron to be tested, Fig. 131, of section area q and peripheral length l, is wound uniformly with Z turns of wire through which the magnetizing current i is sent. Another coil of n turns, not shown in the figure, is wound upon the ring and connected with a ballistic

galvanometer. The magnetizing current, furnished by a battery, flows through an ammeter A, a rheostat, so arranged as to enable the observer to produce quick changes in the current, and a reversing switch S.

The magnetomotive force around the iron ring is $4\pi Zi$, which,

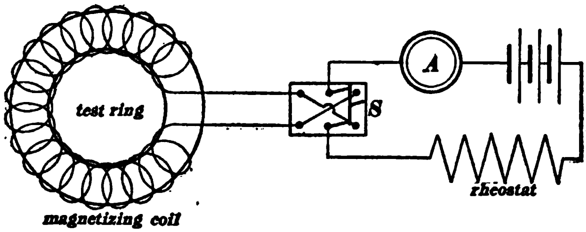

Fig. 131.

divided by the peripheral length of the ring, gives the average magnetizing field $\mathcal{H}$. That is

$$\mathcal{H} = \frac{4\pi Zi}{l} \tag{1}$$

If the current i is suddenly changed by a measured amount Δi, the change in $\mathcal{H}$ is

$$\Delta\mathcal{H} = \frac{4\pi Z}{l} \cdot \Delta i \tag{2}$$

The corresponding change in the flux density $\mathcal{B}$ is

$$\Delta\mathcal{B} = \frac{k'd}{nq} \tag{3}$$

in which k' is the reduction factor of the ballistic galvanometer (see page 18), and d is the observed throw of the ballistic galvanometer needle produced by the change in $\mathcal{B}$.

Proof of equation (3). — The changing flux through the iron ring induces in the n turns of wire, an electromotive force equal to $n \cdot \frac{d\Phi}{dt}$. This electromotive force produces, in the ballistic galvanometer circuit, a current which by Ohm's law is equal to $\frac{\text{electromotive force}}{\text{resistance}}$, and which is also equal to the rate, $\frac{dQ}{dt}$, at which charge passes through the ballistic galvanometer. Therefore

$$\frac{dQ}{dt} = \frac{n}{R} \cdot \frac{d\Phi}{dt}$$

or

$$Q = \frac{n}{R} \cdot \Delta\Phi \tag{4}$$

where Q is the charge that passes through the ballistic galvanometer while the magnetic flux through the iron changes by the amount $\Delta\Phi$ or while the flux density $\mathcal{B}$ changes by the amount

$$\Delta\mathcal{B} = \frac{\Delta\Phi}{q} \tag{5}$$

From the equation of the ballistic galvanometer for measuring charge we have

$$Q = kd \tag{6}$$

Substituting the value of $\Delta\Phi$ from equation (5), and the value of Q from equation (6) in equation (4), writing k' for kR, and solving for $\Delta\mathcal{B}$, we have

$$\Delta\mathcal{B} = \frac{k'd}{nq}$$

The curve of $\mathcal{B}$ and $\mathcal{H}$ may be plotted from a series of observed values of $\Delta\mathcal{H}$ and $\Delta\mathcal{B}$ as follows: Beginning at any point, lay off $\Delta\mathcal{H}$ and $\Delta\mathcal{B}$ to scale. This determines the next point of the curve. From this point lay off the next observed values of $\Delta\mathcal{H}$ and $\Delta\mathcal{B}$, thus locating the next point of the curve, and so on. The whole curve is thus drawn and the axes of $\mathcal{B}$ and $\mathcal{H}$, if it is desired to indicate them, can be drawn through the center of the figure parallel to $\Delta\mathcal{B}$ and $\Delta\mathcal{H}$ respectively.

The most troublesome errors in this method are the following:

1. The magnetizing field, equation (1), is greater in the inner portion of the ring where l is smaller. This lack of uniformity in the magnetizing field introduces complications not considered in equations (2) and (3), and these equations will, therefore, in general, give erroneous results. These errors are in great part obviated by using a ring of such dimensions that l differs but little in various parts of it, and by using a mean value for l in equation (1).

2. Equation (3) takes account only of changes in $\mathcal{B}$ which occur promptly, during an interval of time which is but a fraction of the time of vibration of the ballistic needle.

In some kinds of iron (very soft wrought iron) a quick change in $\mathcal{H}$ produces a prompt change in $\mathcal{B}$, followed by a sluggish change which continues for a few seconds. Equation (3) in this case leads to slightly erroneous results.

Any slow change in the magnetizing current, due, for example, to heating of the wires in circuit or to the polarization of the battery, produces a corresponding slow change in $\mathcal{H}$ and $\mathcal{B}$, in which case also the use of equation (3) leads to erroneous results.

Standardization of the ballistic galvanometer.—This is done by the method described on page 19. Figure 132 shows the

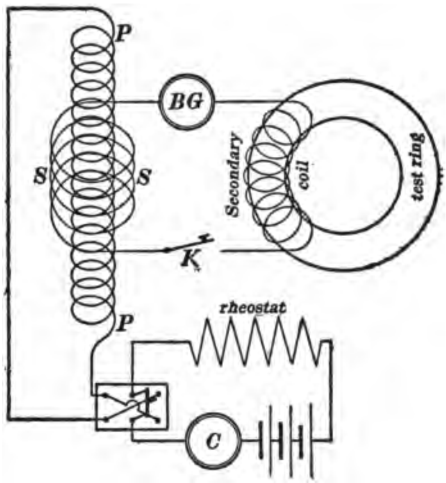

Fig. 132.

complete connections for standardizing. *PPSS* is a Thomson standardizing coil and *C* is an ammeter. The key *K* should be within convenient reach of the observer at the ballistic galvanometer telescope. This key may be opened while preliminary current reversals and changes are being made. When everything is ready for the standardizing observations, close the key *K* and wait for the ballistic galvanometer to become quiet, then observe the ammeter *C*, break the current and observe the ballistic galvanometer throw. Let i' be the ammeter read-

ing and d' the observed throw. Then the reduction factor of the ballistic galvanometer is

$$k' = \frac{4\pi^2 r^2 n' z i'}{d'} \tag{7}$$

in which r is the mean radius of PP, z is the number of turns of wire per unit length of PP, and n' is the total number of turns of wire in the coil SS.

Performance of test.—Figure 131 shows the battery connections while carrying out the test. Leave the ballistic galvanometer circuit as in Fig. 132, and connect up battery circuit according to Fig. 131. Cut out all resistance in the special rheostat and adjust the circuit so that the current is about 3 amperes. Then choose such a number of secondary turns on the test ring that the ballistic galvanometer is not thrown off the scale by reversing the current. The special rheostat is constructed to give approximately the following current steps: 3, 1.5, 0.75, 0.37, 0.18 and 0.09 amperes. The reversing switch has two positions which will be designated as position *A* and position *B*. There are twelve steps in the test, as follows:

(1) Adjust rheostat to give maximum current and reverse the current several times, finally leaving the switch in position *A*. Keep key *K*, Fig. 132, open during these reversals. Then read the ammeter, observe the ballistic galvanometer throw produced when the current is suddenly reduced to 1.5 amperes, and again read the ammeter.

(2) Adjust rheostat to give maximum current and reverse the current several times, leaving the switch in position *A*. Then read the ammeter, observe galvanometer throw when current is suddenly reduced to 0.75 ampere, and again read the ammeter.

(3, 4, 5) Proceed in exactly the same manner for the current steps 0.37, 0.18 and 0.09.

(6) Adjust rheostat to give maximum current and reverse the current several times, leaving the switch in position *A*. Read the ammeter and observe the galvanometer throw when the current is suddenly reduced to zero by breaking the circuit.

Before each of the following observations adjust the rheostat to give maximum current, reverse the current several times, leaving the switch in position A, break the circuit, and set the reversing switch in position B.

(7) Adjust the rheostat to give 0.09 ampere, close the circuit, observe galvanometer throw, and read ammeter.

(8) Adjust the rheostat to give 0.18 ampere, close the circuit, observe galvanometer throw, and read ammeter: (9, 10, 11) and so on step by step until the last observation, namely:

(12) Adjust the rheostat to give maximum current, close the circuit, observe the galvanometer throw, and read the ammeter.

Arrange these observations in tabular form as follows: The current values are entered to show approximately how they run. It is quite important to keep the maximum current the same throughout the test. If the battery runs down, the circuit must be occasionally readjusted. The zero reading of the ballistic galvanometer should be recorded each time and also the actual elongation reading. The difference of these gives the throw. Each value of $\Delta\mathcal{H}$ is calculated by equation (1) from the difference between the corresponding current values.

Each value of $\Delta\mathcal{B}$ is calculated from equation (3). Substituting the value of k' from equation (7) in equation (3) we have

$$\Delta\mathcal{B} = \frac{4\pi^2 r^2 n' z i'}{d' n q} \cdot d \qquad (8)$$

in which r is the mean radius of the coil PP, Fig. 132, z is the number of turns of wire per unit length of PP, n' is the total number of turns of wire in coil SS, i' is any current in PP, the breaking of which gives a throw d' of the galvanometer needle, n is the number of turns of wire in the secondary coil on the test-ring, and q is the sectional area of the iron ring.

Note. — In this discussion current is expressed in c.g.s. units.

In plotting the curves for $\mathcal{B}$ and $\mathcal{H}$ it is to be remembered that all values of $\Delta\mathcal{B}$ and $\Delta\mathcal{H}$ are measured from the same starting point for observations 1 to 6, and all values of $\Delta\mathcal{B}$ and

No.	Current.	Zero Reading of *BG*.	Elongation of *BG*.	Throw of *BG*.	$\Delta\mathcal{H}$	$\Delta\mathcal{B}$
1	3.010*A*					
	1.522*A*					
2	3.010*A*					
	0.762*A*					
3	3.010*A*					
	0.380*A*					
4	3.010*A*					
	0.177*A*					
5	3.010*A*					
	0.088*A*					
6	3.010*A*					
	0.000					
7	0.000					
	0.089*B*					
8	0.000					
	0.178*B*					
9	0.000					
	0.380*B*					
10	0.000					
	0.760*B*					
11	0.000					
	1.521*B*					
12	0.000					
	3.010*B*					

$\Delta\mathcal{H}$ are measured from the point p for observations 7 to 12, p being the point reached by observation 6. One limb of the $\mathcal{B}$ and $\mathcal{H}$ curve is thus plotted. The other limb is exactly similar to it.

Determine the area of the $\mathcal{B}$ and $\mathcal{H}$ curve and calculate the ergs per c.c. per cycle lost in the iron for the given range of $\mathcal{B}$, and also calculate the value of the coefficient in Steinmetz's equation, page 118.

EXPERIMENT 98.

MEASUREMENT OF INTENSE MAGNETIC FIELD BY MEANS OF THE BALLISTIC GALVANOMETER.

The object of this experiment is to measure the intensity of the magnetic field in the small gap-space between the poles of a horse-shoe magnet or in the small gap-space of a dynamo.

Theory of the method. — A flat exploring coil is connected to the ballistic galvanometer, placed in the region where the field intensity $\mathcal{H}$ is to be measured so that the plane of the coil is at right angles to $\mathcal{H}$, and the throw d of the galvanometer is observed when the coil is suddenly jerked out of the region to a place where $\mathcal{H}$ is zero. Then

$$\mathcal{H} = \frac{k'd}{An} \tag{1}$$

in which k' is the reduction factor of the ballistic galvanometer, n is the number of turns of wire in the exploring coil, and A is the area of the mean turn. This equation is evident when we consider that $\mathcal{H}A$ is the magnetic flux per mean turn, and that this flux is reduced to zero when the exploring coil is jerked out of the field. (See page 18.)

The most satisfactory method for standardizing the ballistic galvanometer is that which is described on page 19. In carrying out this standardization the exploring coil, the secondary coil SS, and the ballistic galvanometer should be connected in series so that the galvanometer circuit may be identically the same during the standardization and during the observation of d of equation (1).

Work to be done. — Determine the intensity of the magnetic field in the region between the poles of a horse-shoe magnet and determine the intensity of the magnetic field in the gap-space of a dynamo.

EXPERIMENT 99.

Comparison of Electrostatic Capacities.

The object of this experiment is to determine with the utmost accuracy the ratio of the capacities of two condensers by Kelvin's method of mixtures.

Theory of method. — In Experiment 71 the ratio of the capacities of two condensers is determined by comparing the deflections produced by discharging the condensers through a ballistic galvanometer, the charging electromotive forces being equal, or in a known ratio. The essential steps in Kelvin's method are as follows: A battery produces a constant current i through a circuit as shown in Fig. 133. The two condensers C and C'

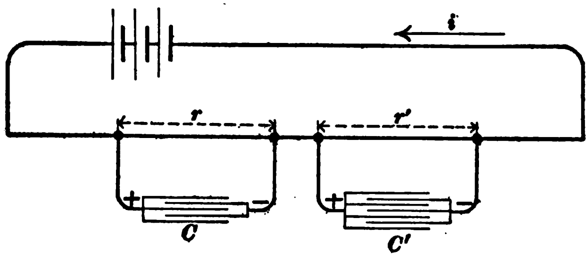

Fig. 133.

to be compared are connected as shown, and the resistances r and r' are adjusted until the charges on the condensers are equal. Then since $q = eC = riC$ and $q' = e'C' = r'iC'$, we have, when $q = q'$:

$$\frac{C}{C'} = \frac{r'}{r} \qquad (1)$$

so that the ratio of the two capacities is determined in terms of the ratio of two resistances. In order to show that the charges on the two condensers are equal, arrangements are made for quickly disconnecting the condensers, connecting them together again as shown in Fig. 134, and then connecting the wires ww

to a sensitive ballistic galvanometer. If the charges on the condensers are equal, the ballistic galvanometer will give no deflection, that is to say, each condenser will discharge into the other, or in other words, the *mixing* of the charges of the two condensers entirely neutralizes both. A convenient arrangement of the apparatus for carrying out Kelvin's method of mixtures is shown in Fig. 135; B is the battery which produces the current i through the resistance boxes R and R'. The condenser C is connected across the terminals of R and the condenser C' is

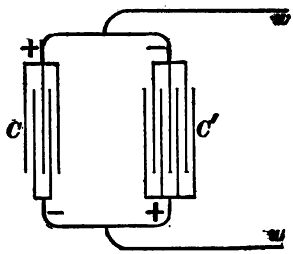

Fig. 134.

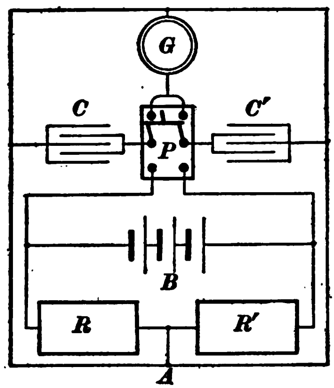

Fig. 135.

connected across the terminals R' when the double-pole double-throw switch P is thrown *down* in the figure. To disconnect the condensers and connect them as shown in Fig. 134, the switch P need only be thrown *upwards*. It is desirable to have a key in the galvanometer circuit which can be closed immediately after the switch P is thrown upwards, otherwise one side of the switch P may close before the other, giving a sudden movement of the galvanometer which is confusing. The parts of the switch P must be very thoroughly insulated from each other.

It is desirable to use a fixed resistance of say 1,000 ohms for R and an adjustable resistance box for R'.

Work to be done. — Connect a standard condenser and a given condenser as shown in Fig. 135, and adjust the resistance boxes

R and R' until the galvanometer gives no deflection when the switch P is thrown up.

Determine in this way the capacity of several given condensers in terms of the capacity of a standard condenser.

EXPERIMENT 100.

Measurement of Insulation Resistance by Leakage.

The object of this experiment is to determine the insulation resistance of a condenser or of a lead-incased cable by observing the loss of charge by leakage when the condenser or cable is charged and allowed to stand.

Theory. — Let C be the capacity of the condenser and Q the amount of charge which is forced into it when it is connected to a charging electromotive force E. Then we have

$$Q = CE \tag{1}$$

The condenser (or cable) is then allowed to stand for t seconds during which time the charge leaks off through the insulation resistance R, and the charge which remains is

$$q = CE\epsilon^{-\frac{t}{CR}} \tag{2}$$

The ratio q/CE may be determined as follows: Charge the condenser with electromotive force E, discharge it immediately through a ballistic galvanometer, and observe the throw D. Then charge the condenser afresh, allow it to stand for t seconds, discharge it through the ballistic galvanometer and observe the throw d. Then $q/CE = d/D$, which substituted in equation (2) gives

$$R = \frac{t}{C(\mathrm{Log}_\epsilon D - \mathrm{Log}_\epsilon d)} \tag{3}$$

whence R is known when C is known, t, d and D being observed.

A serious source of error in this method is that a freshly

charged condenser apparently loses charge because of the soaking-in effect which is described in Experiment 72, and this apparent loss of charge cannot be distinguished from loss of charge due to actual leakage. This difficulty may be partly overcome by leaving the electromotive force connected to the condenser for, say, five minutes each time the condenser is charged. Then the soaking-in action will be nearly completed while the battery is connected.

Equation (2) is derived as follows: When the charge on the condenser has decreased to the value q the electromotive force e across the condenser terminals is q/C, which divided by the resistance R gives the leakage current $(= - dq/dt)$ so that

$$-\frac{q}{CR}=\frac{dq}{dt}$$

The integration of this equation from $q = CE$ to $q = q$ gives equation (2).

Work to be done. — Charge a condenser for five minutes and discharge it through a ballistic galvanometer observing the throw D. Charge the condenser again for five minutes, disconnect the battery and let the condenser stand carefully insulated for half an hour. Then discharge the condenser through the ballistic galvanometer and observe the throw d.

If the value of d as above determined is nearly as large as D, repeat the above procedure, allowing the condenser to stand for an hour or two before taking the second deflection.

Computations and results. — Calculate the value of the insulation resistance of the condenser from the above data.

EXPERIMENT 101.

MEASUREMENT OF INDUCTANCE BY WHEATSTONE'S BRIDGE.

The object of this experiment is to determine the value of the coefficient of self-induction of a coil of wire.

Theory. — The inductance X to be measured is connected in series with an adjustable non-inductive resistance r in one arm of the Wheatstone's bridge, as shown in Fig. 136. A variable

standard of self-inductance S is connected in the other arm of the bridge. (*a*) The two ratio arms of the bridge α and β are adjusted to give no deflection of the galvanometer G when the bridge is supplied with current from a battery, and then (*b*) the variable standard of self-inductance is adjusted until the sound in the telephone T is a minimum when the bridge is supplied

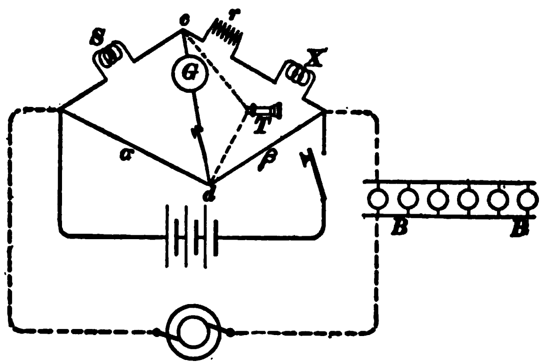

Fig. 136.

with alternating current as indicated by the dotted connections in the figure.

When these two adjustments have been made, the two inductances S and X are to each other as α and β, so that

$$X = \frac{\beta S}{\alpha} \tag{i}$$

The truth of this equation is evident from the following considerations: (1) The electromotive force between the terminals of the telephone is zero in so far as the RI drops of voltage in the four arms of the bridge are concerned, when adjustment (*a*) has been completed. (2) Adjustment (*b*) gives zero current through the telephone and therefore exactly the same alternating current must flow through S and X. Let di/dt be the rate of change of this current, then $S \times di/dt$ is the inductance drop of voltage across S, and $X \times di/dt$ is the inductance drop of voltage across X, and these two voltage drops must be in the same

ratio as the RI drops in α and β to give zero electromotive force across cd, Fig. 136, so that S/X equals α/β.

Accuracy in the use of the Wheatstone bridge demands approximate equality of the two bridge arms. The adjustable non-inductive resistance r is therefore introduced in order that the resistances of the two arms S and X may be made approximately equal.

In order that the ratio α/β may not differ greatly from unity,

Fig. 137.

it is necessary to be able to adjust the inductance S through a wide range. Therefore it is desirable to use a set of fixed standards of self-inductance any one or all of which may be connected in series with X.

A convenient form of adjustable standard of self-induction is that of Ayrton and Perry, a general view of which is shown in Fig. 137. The fundamental idea of this device is as follows:

Two coils consisting of wires wound "along the parallels of latitude" of two concentric spheres and connected in series would have a total inductance which could be easily calculated and which would vary according to a simple and well-known function of the angle between the axes of the two spheres. The Ayrton and Perry device is constructed so as to approximately realize this idea, and the value of the combined inductance of the two coils is indicated by the divided scale on the top of the instrument.

Work to be done. — Connect up the coil of which the inductance is to be measured, the standard of self-inductance S, and the adjustable non-inductive resistance r, as shown in Fig. 136. Make α and β approximately equal to each other and adjust the non-inductive resistance r until the galvanometer gives no deflection when the bridge is supplied with direct current. Then replace the galvanometer by the telephone, connect the bridge to an alternating-current supply, using a lamp bank BB as a rheostat, and adjust S until the sound in the telephone is a minimum.

If this second adjustment should be found to be beyond the range of S, insert fixed standards of self-inductance in series with S, repeat the first adjustment, and make another trial of the second adjustment with alternating current. It is allowable to use values of the ratio α/β ranging from .7 or .8 to 1.2 or 1.3 without introducing excessive errors in the result.

(*a*) Measure the inductance of a given coil not having an iron core.

(*b*) Repeat (*a*) with sheets of copper placed over the ends of the coil.

(*c*) Measure the inductance of the primary coil of a transformer with the secondary coil opened and then with the secondary coil closed.

Note. — The telephone is not sufficiently sensitive to permit of very accurate adjustment of the bridge arrangement shown in Fig. 136. Other forms of alternating current galvanometer* are

* The *Vibration galvanometer*, devised by Max Wein, is described in *Annalen der*

available but they are not convenient in use. The best arrangement perhaps is to drive a rectifying commutator in synchronism with the alternating current which is supplied to the bridge, to use this commutator for rectifying the alternating current which flows across *cd*, and to deliver this rectified current to a very sensitive direct-current galvanometer.

EXPERIMENT 102.

Comparison of Capacities by Wheatstone's Bridge.

The object of this experiment is to determine the ratio of the capacities of two condensers by means of the Wheatstone bridge, the purpose being to determine the inductivity of a dielectric.

Theory of the method. — The two condensers C and c to be compared are connected as shown in Fig. 138, the two bridge

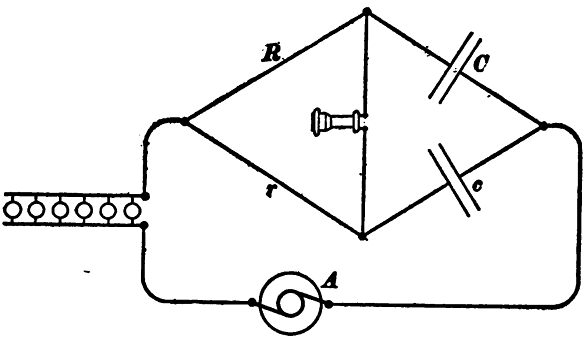

Fig. 138.

arms R and r being non-inductive. The ratio R/r is adjusted until the telephone gives a minimum sound and then the relation $R/r = c/C$ holds, so that the ratio of the capacities of the two

Physik, Vol. 4, page 439, March, 1901. See *Note on the vibration galvanometer* by R. T. Wells, *Physical Review*, Vol. 23, page 504, December, 1906.

An extremely sensitive type of alternating-current galvanometer devised by W. S. Franklin and L. A. Freudenberger is described on page 37, Vol. 24, of the *Physical Review*, January, 1907.

condensers is known. This relation is evident from the following considerations : The same alternating current I flows through R and C (and the same alternating current i flows through r and c) when the telephone gives no sound, and the RI drop through R must be equal to the RI drop through r when no current flows through the telephone, therefore

$$RI = ri \tag{i}$$

at each instant. Let Q be the charge in condenser C at a given instant and q the charge in condenser c at the same instant. Then the voltage across C is Q/C and the voltage across c is q/c and these two voltages must be equal. Therefore,

$$Q = \frac{C}{c}q \tag{ii}$$

but $I = dQ/dt$ and $i = dq/dt$, whence from equation (ii) we have

$$I = \frac{C}{c} \cdot i \tag{iii}$$

and, substituting this value of I in equation (i), we have

$$\frac{R}{r} = \frac{c}{C} \tag{iv}$$

In order to secure a moderate degree of sensitiveness of adjustment in the apparatus shown in Fig. 138 when the condensers C and c are both of moderately small capacity, it is necessary to use a very high alternating voltage, the resistances R and r must be large, and the telephone should be wound with extremely fine wires so that its sensitiveness may be high. A sensitive direct-current galvanometer and a rectifying commutator may be used instead of a telephone as explained in Experiment 101.

Determination of inductivity.—The capacity of a condenser consisting of parallel metal plates each having a square centi-

meters of area and separated by a layer of insulator x centimeters thick is given by the equation

$$C' = \frac{ka}{4\pi x}\ * \tag{v}$$

in which k is the inductivity of the dielectric. For air k equals unity. Therefore if the two condensers C and c in Fig. 138 are made of flat metal plates, we have

$$\frac{C}{c} = \frac{\dfrac{kA}{4\pi X}}{\dfrac{a}{4\pi x}} = \frac{kAx}{aX} \tag{vi}$$

in which k is the inductivity of the dielectric in the condenser C, the condenser c being an air condenser. Therefore from equation (vi) we have

$$k = \frac{aX}{Ax} \times \frac{C}{c} \tag{vii}$$

so that the inductivity of the dielectric is known when the ratio C/c, the distances X and x, and the areas A and a have been measured.

Apparatus.—The air condenser c to be used consists of flat metal plates one of which can be moved parallel to itself by means of a micrometer screw so that the distance x can be varied at will and accurately measured. The condenser C consists of two metal plates pressed against the two sides of a flat plate of the dielectric of which the inductivity is to be determined, a piece of hard rubber or a piece of glass, for example. The bridge arms R and r are fixed in value, and the adjustment to give a minimum sound in the telephone is accomplished by adjusting the distance x between the plates of the air condenser. In order to obtain a degree of sensitiveness which will permit even of very rough measurements by the use of a moderate alternating

* The units in terms of which the capacity is given by this equation are of no present consequence.

voltage, the plate of the dielectric must be quite thin, the areas of the plates in both condensers C and c must be quite large, and a high frequency alternating current must be used. The most convenient source of high frequency current for this purpose is an induction coil with a coarse wire secondary, the primary of which is supplied with current through a Wehnelt interrupter.

Work to be done. — Measure the areas of the condenser plates and the thickness of the sample of dielectric, glass or hard rubber as the case may be. Connect up the apparatus as indicated by Fig. 138, using an induction coil excited by a Wehnelt interrupter for supplying the alternating current. Adjust the air condenser until the sound of the telephone is reduced to a minimum and measure the distance x between the plates of the air condenser. Proceed in the same way with several samples of insulating materials.

Computations and results. — Calculate the inductivity of each sample of dielectric from the observations above obtained.

EXPERIMENT 103.

Study of Electrolytic Polarization. Decomposition Voltages.

The object of this experiment is to determine the critical voltage of decomposition of a given electrolyte between given electrodes.

Theory. — Consider an electrolytic cell of any type, for example, a solution of dilute sulphuric acid between platinum electrodes. When current flows through this cell water is decomposed, hydrogen appears at one electrode and oxygen at the other. If the amount of water decomposed were strictly proportional to the current and to the time, then no current whatever would flow through the cell until the impressed voltage exceeds a certain critical value which is called the *decomposition voltage* for the given combination of electrodes and electrolyte. As a matter of fact, however, current flows through the cell however small the impressed electromotive force may be, and this current does not

produce actual decomposition. The hydrogen ions which are carried into the neighborhood of the cathode are acted upon by traces of free oxygen in solution forming water, and the SO_4 ions which are carried into the neighborhood of the anode are combined with the traces of free hydrogen in solution forming H_2SO_4 with the result that the solution remains entirely unchanged as the current continues to flow.

The continued flow of current through an electrolytic cell when the electromotive force is less than the critical value depends in the above case upon the continued supply of dissolved oxygen and hydrogen by diffusion from the body of the solution into the neighborhood of the electrodes, a process which is independent of the value of the impressed voltage. Therefore the value of

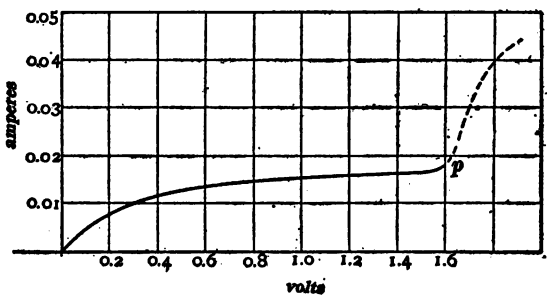

Fig. 139.

the current due to a given impressed voltage (less than the decomposition voltage) is approximately independent of the voltage after the current has been flowing for a very long time so that a steady state of diffusion is set up, *except when the impressed voltage is very small,* in which case the diffusion is capable of supplying dissolved oxygen and hydrogen more rapidly than it is used up in the neighborhood of the electrodes. Therefore, if a series of voltages are made to act upon an electrolytic cell and the corresponding currents observed after the lapse of very long intervals of time so as to permit of the cell to settle to a steady state of diffusion, the relation between voltage and current would be somewhat as shown by the curve in Fig. 139.

When, however, the impressed voltage reaches a value at which oxygen and hydrogen begin to be liberated at the electrodes a very sudden rise of current takes place as shown by the dotted portion of the curve in Fig. 139.

The value of the decomposition voltage for a given electrolytic cell may therefore be determined by carefully plotting the curve of voltage and current and determining as accurately as possible the voltage corresponding to the sharp bend *p*, Fig. 139.

Apparatus. — A slide wire *ab*, Fig. 140, having about half an ohm resistance is connected through a rheostat *R* to a supply

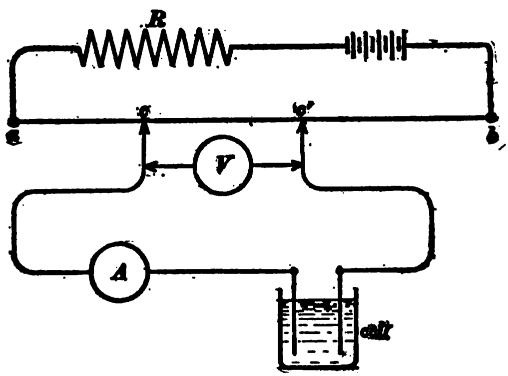

Fig. 140.

of direct current and the rheostat is adjusted to give about 5 or 6 amperes in the wire. An ammeter *A* having a wide range * is connected in series with the electrolytic cell which is to be studied; and various impressed voltages are applied to the circuit by moving the sliding contacts *cc'* in Fig. 140, the value of the voltage being indicated by the voltmeter *V*.

Work to be done. — Set up an electrolytic cell containing clean dilute sulphuric acid and clean platinum electrodes, arranging the apparatus as shown in Fig. 140.

Connect a certain voltage *V*, observe the ammeter readings

* A D'Arsonval galvanometer with a series of shunts will be found to be most suitable as an ammeter.

at intervals of a minute or so for a period of 15 or 20 minutes so as to get an idea of the approximate value of the steady current corresponding to the given voltage.

Repeat this set of observations for a series of voltages ranging from about .1 of a volt to about 2 volts.

Note the approximate voltage at which a sudden rise of current takes place and for which bubbles of oxygen and hydrogen begin to appear and observe values of current (ultimate) for a series of voltages in the immediate neighborhood of this value.

Computations and results. — (*a*) Plot a series of curves of which the abscissas represent elapsed times and the ordinates represent the corresponding observed values of current for each value of the voltage.

(*b*) Plot a curve of which the abscissas represent voltage values and the ordinates the corresponding ultimate values of the current and locate as accurately as possible the sharp bend in the curve and the corresponding value of the voltage.

Note. — The ultimate value of the current which flows through an electrolytic cell on account of diffusion is reached only after very long periods of time, sometimes days or weeks, and it is therefore impossible to determine the actual ultimate values of the current in this experiment. If the curves of current and time mentioned under (*a*) above become approximately horizontal after ten minutes or so, the ordinate of this horizontal portion may be taken as the approximate ultimate value of the current.

EXPERIMENT 104.

USE OF THE NORMAL ELECTRODE FOR DETERMINING ELECTROLYTIC POLARIZATION.

The object of this experiment is to determine the electromotive force or potential difference between a single electrode and an electrolyte.

Theory. — The difficulty of measuring the electromotive force between an electrode and an electrolyte is that an elaborate de-

vice (the dropping electrode) must be used to make connection to the electrolyte in such a way as to avoid a potential difference at the point of contact as well as at the electrode. Any ordinary point of contact constitutes a second electrode, and the electromotive force that is measured is therefore the total electromotive force of two electrodes and not the electromotive force between one electrode and the solution.

The *dropping electrode* consists of a fine jet of mercury which breaks up into drops. Such an electrode always settles to the same potential as the electrolyte if it is fairly well insulated, because if there is any potential difference between the mercury and the solution, a large amount of charge accumulates on the surface of the mercury drops and this charge is drawn out of the system (electrometer) to which the jet is connected until the whole system is at the same potential as the solution.

Ostwald's normal electrode. — Using the dropping electrode, Ostwald determined the potential difference between an electrode of pure mercury and a normal * solution of potassium chloride when the mercury was covered with a paste of pure mercurous chloride (HgCl). This potential difference or electromotive force is 0.56 volt, and it tends to cause an electric current to flow from the solution into the mercury electrode.

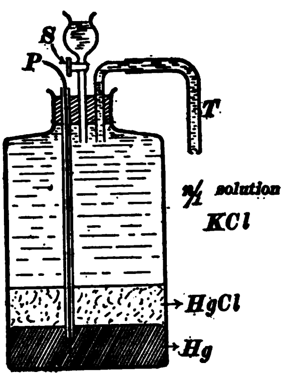

FIG. 141.

By means of this normal electrode potential differences between metals and electrolytes can be easily measured. For example, let it be required to determine the potential difference between magnesium metal and a normal solution of magnesium chloride. The magnesium chloride and the magnesium electrode are placed in a beaker, the normal electrode is arranged

* A normal solution of a salt is a solution which contains in each liter a number of grams of the salt equal to its molecular weight. Thus, a normal solution of potassium chloride contains 74.6 grams of the anhydrous salt per liter.

as shown in Fig. 141, the tube *T* is dipped into the magnesium chloride solution, thus forming a complete electrolytic cell, Hg — KCl — MgCl — Mg. The electromotive force of this cell is found by measurement to be 1.791 volts in the direction (inside the cell) from the magnesium to the mercury so that the electromotive force between the magnesium electrode and the solution is 1.791 − 0.56, or 1.231 volts; on the assumption that there is no potential difference between the magnesium chloride solution and the potassium chloride solution. In fact, there is always a slight electromotive force at the point of contact of different solutions.

Work to be done. — Measure the electromotive force between a normal solution of sulphuric acid (98 grams H_2SO_4 per liter) and the following electrodes: clean zinc, amalgamated zinc, copper, and iron.

The tube *T* should be rinsed out immediately after a measurement has been made by opening the stop-cock *S* and allowing fresh potassium chloride solution to flow into the bottle, thus forcing the impure solution out of the tube *T*. The end of the tube *T* should be slightly contracted so that the solution may not flow out of it, and when the apparatus is not in use the end may be covered with a bit of beeswax to prevent the solution from evaporating and depositing solid crystals in the end of the tube.

A voltmeter of very high resistance must be used for this measurement in order to avoid changes of polarization. The best arrangement is to use a fairly sensitive D'Arsonval galvanometer (with a high resistance in series with it) as a direct-reading voltmeter, or a potentiometer.

EXPERIMENT 105.

Relative Migration Velocities. Hittorf's Ratio.

The object of this experiment is to determine the relative velocities of migration of the ions in an electrolyte.

Theory. — The chemical action which takes place during elec-

trolysis occurs wholly in the immediate neighborhood of the electrodes. There is no change in the body of the electrolyte except a rise of temperature due to the heating effect of the current. During the electrolysis of a solution of a salt, $CuSO_4$ for example, the amount of the salt in the solution is diminished if there are no secondary reactions at the electrodes, and after the electrolysis has been kept up for some time a certain total diminution of dissolved salt is produced. Let x grams be the diminution of dissolved salt in the neighborhood of the anode and y grams the diminution of dissolved salt in the neighborhood of the cathode. The ratio x/y, called Hittorf's ratio, has a definite characteristic value * for every electrolytic salt or acid.

In most cases, for example in the electrolysis of $CuSO_4$, the anion, SO_4, reacts upon the solvent and goes into solution. The solution near the anode is then no longer a simple solution of the original salt, but contains in addition the products resulting from breaking up of the anion or the products resulting from the action of the anion upon the solvent, or upon the material of the anode. Thus, if a copper anode is used in the electrolysis of $CuSO_4$, the anion SO_4 attacks the copper anode forming $CuSO_4$ which goes into solution. In this case, the solution in the neighborhood of the anode would have an excess of $CuSO_4$ exactly equal to the diminution of $CuSO_4$ in the neighborhood of the cathode.

Apparatus. — A form of apparatus devised by Mather † for determining Hittorf's ratio is shown in Fig. 142. Two vertical tubes A and B, each about 24 centimeters in length and 2 centimeters in diameter, have contracted portions near the top which are 6 centimeters long and 0.5 centimeter in diameter, and these reduced portions are graduated in millimeters. These two tubes are connected near the upper end of the large parts by a U-tube the bottom of which is about 2 centimeters above the

* In fact, the value of this ratio for a given salt varies slightly with concentration, with temperature, and with current density.

† Dissertation, Johns Hopkins University, 1897.

lower ends of the tubes A and B. At the center of this connecting tube is a stop-cock S of large bore. The lower ends of the tubes A and B are closed by glass stoppers through which holes are bored for the insertion of the electrodes. The apparatus is fixed to a metal frame and arranged so that it can be submerged in a thermostat bath.

Method of determining Hittorf's ratio. — The apparatus shown in Fig. 142 is filled with the electrolyte to be studied to definite points on the two scales at the top of the tubes A and B with the stop-cock open. The stop-cock is then closed and the content of salt in each half of the apparatus A and B is determined by chemical analysis.

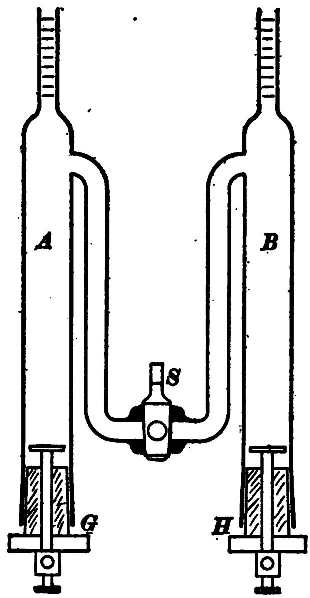

Fig. 142.

The apparatus is again filled with the electrolyte to the same points as before, a known electric current is passed through the cell for a known interval of time, the stop-cock S is closed, and the content of salt in each half of the apparatus A and B is again determined. The diminution of salt in the neighborhood of one of the electrodes is then equal to the total diminution of salt in the half of the apparatus in which that electrode is placed so that Hittorf's ratio is thus found.

Work to be done. — Determine Hittorf's ratio for a normal solution of copper sulphate, using copper electrodes. The content of copper sulphate in the two halves of the apparatus is to be determined by a standard method of volumetric analysis.

Two or three complete determinations should be made, temperature, current density and concentration of solution being the same in every case.

Computations and results. — When secondary reactions take place at the electrodes, due allowance must be made for these reactions in the calculation of the theoretical diminution of salt at each electrode.

Hittorf's ratio may be interpreted in the light of the dissociation theory as the ratio of the velocities of migration of the anions and cathions in the solution as follows: Consider the electrolysis of a solution of $CuSO_4$. Suppose the electrolysis to have continued until 159.3 grams of $CuSO_4$ (1 gram-molecule) have been decomposed, 63.3 grams of copper being deposited on the cathode and 96 grams of SO_4 being liberated at the anode.

If we imagine the current through the electrolyte to depend entirely upon the movement of copper ions, the SO_4 ions being assumed to be stationary throughout the middle portions of the electrolyte, then the solution near the anode will become deficient in $CuSO_4$ by the whole amount of 159.3 grams and the solution will be unchanged in strength everywhere else.

If, on the other hand, we imagine the current through the electrolyte to depend entirely upon the movement of the SO_4 ions, the copper ions being assumed to be stationary throughout the middle portion of the electrolyte, then the solution near the cathode will become deficient in $CuSO_4$ by the whole amount of 159.3 grams and the solution will be unchanged in strength everywhere else.

If the velocity of copper ions is to the velocity of the SO_4 ions as $n : 1$, then $n/(n + 1)$ of the current may be attributed to the movement of the copper ions and $1/(n + 1)$ of the current may be attributed to the movement of the SO_4 ions. On account of the movement of the copper ions the solution in the neighborhood of the anode will become deficient in $CuSO_4$ by the amount of $159.3 \times n/(n + 1)$ grams, since 159.3 is the deficiency at the anode which would be produced if the whole of the current were due to the movement of the copper ions. Similarly, $159.3 \times 1/(n + 1)$ grams is the deficiency in $CuSO_4$ in the neighborhood of the cathode on account of the movement of the SO_4

ions. *Therefore the ratio of these deficiencies is equal to the ratio of the ionic velocities.* It is to be kept in mind in this discussion that as the SO_4 ions move through the electrolyte away from the vicinity of the cathode, the same number of Cu ions are deposited at the cathode without having to travel through the middle portions of the electrolyte. The same is true of the deposit of SO_4 ions at the anode as the copper ions move away from the vicinity of the anode towards the cathode. Thus, if the copper ions and SO_4 ions were to move through the solution at the same velocity, half of the copper which is deposited upon the cathode would travel through the solution from the vicinity of the anode, and half would come from the immediate vicinity of the cathode because of the movement of the SO_4 ions away from this region towards the anode.

EXPERIMENT 106.

Absolute Determination of Migration Velocity.

The object of this experiment is to determine the velocity of migration of the ions in an electrolyte in centimeters per second.

Apparatus. — The apparatus to be used is due to Whetam.* It depends upon the use of an electrolytic cell in which a colorless electrolyte is superimposed upon a colored electrolyte and the movement of the ions is indicated by the change of position of the line of division between the two solutions. Figure 143 shows the essential features of the apparatus.

Work to be done. — Fill the large vessel *BB*, Fig. 143, with a solution of cupric chloride until the solution reaches nearly to the top of the small connecting tube. Then pour a solution of ammonium chloride into the vessel *A*. The connecting tube *U* has a small hole blown at *T* which is stopped with a small bit of beeswax. When the solutions have been poured in as above specified, remove this bit of wax and allow a small quantity of liquid to flow out, thus removing every trace of the mixed liquid and leaving a sharp line of division between the NH_4Cl and the

* *Philosophical Transactions*, 1893*A*, page 337.

$CuCl_2$ solutions at *T*. Then stop the hole at *T* with a bit of wax and pour in an additional amount of NH_4Cl solution until the line of division between the two solutions moves down to a uniform portion of the tube at *U*.

Measure the length of the small connecting tube.

Connect a known electromotive force *E* to the cell, allow the current to flow for a known interval of time, and observe the distance moved by the line of division between the colored and colorless solutions.

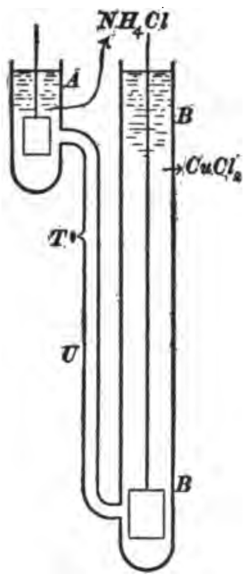

Fig. 143.

Computations and results. — The movement of the line of division between the colored and colorless solutions in the above experiment is due to the motion of the copper ions in the direction of the current. The velocity of the copper ions is equal to av where v is the potential gradient (volts per centimeter) along the connecting tube and a is a constant which depends upon the character of the ions. It is this quantity a which is to be determined, and it is equal to the velocity of the ions in a region where the potential gradient is 1 volt per centimeter. The actual velocity of the ions is found by dividing the movement above observed by the time during which the current continued to flow, and the value of a is found by dividing this actual velocity by the potential gradient v.

The velocity of migration of the ions in an electrolyte per unit of potential gradient [a] may be calculated from the concentration of the solution, its degree of dissociation, Hittorf's ratio and the specific resistance of the solution, as follows:

The discussion is more readily followed if it is made to apply to a particular case. Let us consider therefore an electrolytic cell consisting of flat parallel electrodes in a square jar containing

a solution of $CuSO_4$. Let d centimeters be the distance between the electrodes, A square centimeters the area of each electrode, and ρ the specific resistance of the solution. Then $\rho d/A$ is the resistance of the cell, and E divided by $\rho d/A$ is the current flowing, E being the electromotive force acting on the cell. Furthermore, k times the current $(EA/\rho d)$ is the rate at which copper is deposited on the cathode in grams per second, and $n/(n+1)$ times $kEA/\rho d$ is the portion of this deposit which may be thought of as due to the motion of the copper ions (see page 144), k being the electrochemical equivalent of copper in grams per coulomb and n being the value of Hittorf's ratio for the given solution of $CuSO_4$.

Now all of the ionized copper in the solution is to be thought of as moving towards the cathode at a velocity equal to aE/d centimeters per second, where a is the factor above referred to, and E/d is the potential gradient in the solution. The product of this velocity by the area A, and by the density of the ionized copper in the solution in grams per cubic centimeter is the rate in grams per second at which ionized copper is passing a given plane, or the rate at which copper is deposited on account of that fractional part of the current $[n/(n+1)]$ which is due to the motion of the copper ions. But μcm is the density of ionized copper in grams per liter of the solution so that $\mu cm/1000$ is the density of ionized copper in grams per cubic centimeter of solution, c being the concentration of the solution in gram-molecules of salt per liter, μ the ratio of dissociation of the salt, and m the atomic weight of copper. Therefore

$$\frac{kEA}{\rho d} \cdot \frac{n}{(n+1)} = \frac{aE}{d} \cdot \frac{\mu cm}{1000} \cdot A$$

or

$$a = \frac{1000kn}{\mu cm\rho(n+1)}$$

The values of a calculated from this equation agree satisfactorily with the values determined directly as above.*

* See *Elements of Physical Chemistry*, H. C. Jones, pages 334–337.

EXPERIMENT 107.

Determination of Radio-Activity.

The object of this experiment is to determine the radio-activity of a mineral in terms of the radio-activity of a standard sample of a radio-active substance.

Theory. — The chemical elements, uranium, thorium and radium and their compounds have the property of making a surrounding gas an electrical conductor. Thus, one ten-millionth of a gram of radium bromide left as a residue upon a metal plate by evaporating a small quantity of a dilute solution of radium bromide on the plate, causes a gold leaf electroscope to be discharged in a few seconds when the radium covered plate is held near to the metal plate of the electroscope. Uranium and thorium have the same effect but the discharge which they produce is not so rapid unless a large quantity of material is employed. This property of these metals and their compounds is called *radio-activity,* a name which originated because of the peculiar radiations which are found to emanate from the radio-active substance and to which the discharging action is due. These radiations are of three distinct kinds which are called the α-rays, the β-rays, and the γ-rays, respectively. The γ-rays penetrate through several feet of solid metal or through many meters of air, the β-rays penetrate through a moderate thickness of light metal, such as aluminum, whereas the α-rays are stopped by an extremely thin layer of aluminum or by a layer of air 6 or 7 centimeters in thickness.

The α-rays consist of positively charged particles each about twice as massive as a hydrogen atom. These particles are projected from the radio-active substance at a velocity of about 20,000 miles per second, and each one of them ionizes about 100,000 air molecules before it is brought to rest by repeated collision. After traveling 6 or 7 centimeters through the air the velocity of these α-particles is reduced to so low a value as to render them no longer perceptible by their ionizing effects.

The β-rays consist of negatively charged particles each about one thousandth as massive as a hydrogen atom. These particles are projected from the radio-active substance at a velocity which in some cases approximates to the velocity of light, say 160,000 miles per second. These β-particles also have the property of ionizing the gas through which they pass, but not to so great an extent as the α-particles, and they travel several meters through air before their velocity is reduced to so low a value as to render them no longer perceptible by their ionizing effects.

The γ-rays are extremely abrupt waves in the ether essentially the same as the X-rays, but much more penetrating than ordinary X-rays. These rays also have the property of ionizing a gas but not to so great an extent as either the α-rays or the β-rays.

The α-rays and the β-rays are deflected by magnetic fields and by electric fields. The direction of the deflection of the α-rays is in each case opposite to the direction of deflection of the β-rays, and therefore it is known that the α-particles are positively charged and the β-particles are negatively charged. The γ-rays are not deflected by a magnetic field or by an electric field.

The present hypothesis regarding radio-activity is that the atoms of all substances are complex systems of excessively small particles called *electrons*, the atom of each element being a characteristic self-contained group or system of electrons in very violent orbital motion. These systems of electrons (atoms) are supposed to be to some extent unstable, and when instability occurs, the system (atom) collapses into a new configuration and at the same time expels one or more positively or negatively charged electrons or groups of electrons which constitute the α-rays and the β-rays. The γ-rays according to this hypothesis consist of abrupt ether waves which are produced by the sudden collapse of the atomic structure when instability occurs.*

* This outline of the facts and theories of radio-activity is given here in order that the student may have some idea of what he is doing in his determination of radio-activity. The student is referred to Radio-activity by E. Rutherford, Cambridge, 1905 (2d edition); Radio-activity by Frederick Soddy, London, 1904; and to Radio-active Transformations, by E. Rutherford, New York, 1906, for a full discussion of this subject.

An ideal arrangement for measuring the radio-activity of a substance would be that shown in Fig. 144, in which *AA* and *BB* are metal plates and *MM* is a layer of radio-active material spread over the plate *AA*. The radiations from the material ionize the air between the plates, and the electric field between the plates due to the battery *b* causes all of the positively-charged ions to move in one direction and all of the negatively-charged ions to move in the opposite direction, thus constituting an electric current which is indicated by the galvanometer *G*. This electric current depends to some extent upon the electromotive force of the battery. When the electromotive force of the battery is very small, many pairs of positive and negative ions recombine to form neutral air molecules before they reach the plates, and therefore all of the ions do not contribute equally to the flow of current. When, however, the electromotive force of the battery *b* is sufficiently great (three or four hundred volts), nearly all of the ions that are formed by the radiations from the substance *MM* contribute to the carrying of electric charge across from plate to plate, and when this value of electromotive force is reached a very considerable increase of the electromotive force produces little or no increase of current. This maximum current is called the *saturation current;* it is proportional to the total number of ions produced per second by the radiations from the material *MM*, and it may be taken as a measure of the radio-activity of the substance *MM*. When the electromotive force of the battery *b* is increased more and more, a value is eventually reached for which the moving ions of the air gain sufficient velocity during the time between successive collisions with air molecules and with each other to produce fresh ions from neutral air molecules, and when this point is reached the current begins to rise rapidly with further increase of electromotive force. This is shown by the

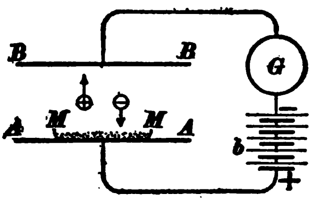

Fig. 144.

curve in Fig. 145, in which the ordinates represent to an arbitrary scale the values of the current and the abscissas represent the corresponding values of the electromotive force in volts between the plates *AA* and *BB*.

The simple method outlined above for measuring radio-activity is not generally feasible because of the excessively small current to be measured, a smaller current than would produce a sensible deflection upon the most sensitive galvanometer. The method usually employed is to determine the current carried across from plate to plate in Fig. 144 by observing the rate of discharge of a gold-leaf electroscope or of a quadrant electrometer. In this way a current of two one-thousand-million-millionths of an ampere can be measured with considerable accuracy.

Fig. 145.

Figure 146 shows a gold leaf electroscope arranged for measuring radio-activity. *AA* is a metal plate upon which the radioactive material is spread. *BB* is an insulated metal plate fixed to the metal rod *R*, to the side of which an aluminum or gold leaf *L* is attached. The rod *R* is cemented into a hard-rubber bushing by pouring melted sulphur around it (it is important not to heat the sulphur too hot in melting it). A metal rod *C* turns loosely in a hard rubber bushing, and it is arranged so that it can be brought into contact with the rod *R* in order to charge *L*, *R* and *B*, after which the rod *C* may be disconnected from *R*

and turned so as to come into contact with the metal lining of the containing case (the entire containing case should be lined with metal).

The plates AA and BB are enclosed in a chamber in one side of which is a door through which the tray containing the radio-active material may be introduced or removed at will.

The case which encloses the leaf L has a window through which the gold leaf can be observed by means of a reading microscope.* As the system LRB loses its charge, the leaf moves across the field of view of the reading microscope, and the observation consists of the determination of the interval of time required for a specified movement of the leaf.

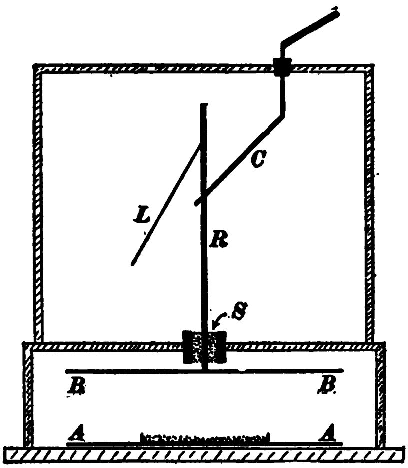

Fig. 146.

The indications of the apparatus shown in Fig. 146 depend almost solely upon the α-rays inasmuch as about 99 per cent. of the ionization of the air between the plates AB is due to the α-rays. When it is desired to investigate radio-activity by means of the ionizing effect of the β-rays, the radio-active material is covered with a thin sheet of metal so as to screen off the α-rays; and when it is desired to investigate radio-activity in terms of the ionizing effect of the γ-rays, the α-rays and the β-rays must be screened off by means of a very thick layer of a substance such as lead.

* Perhaps the most convenient device for indicating the position of the leaf L is to cut windows in opposite sides of the containing case, place a kerosene lamp near to one of these windows, and project an image of the leaf L upon a translucent screen by means of a lens. A divided scale can be marked upon the translucent screen and the position of the gold leaf read off with considerable accuracy.

Work to be done. — Set up the electroscope as shown in Fig. 146, charge the system *LRB* by means of a small piece of hard rubber or sealing wax rubbed against the coat sleeve, and disconnect the rod *C*.

(*a*) Observe the time t required for the leaf to move over a specified distance when no radio-active material is on the plate *A*. The reciprocal of this time interval may be used as a measure of the current which leaks off the charged system on account of the imperfect insulation which is due indeed to the "natural" ionization of the air.

(*b*) Place upon the plate *A* a tray containing *W* grams of powdered uranium oxide (costs ten dollars per pound!) spread out in a uniform layer not less than 0.5 mm. thick, charge the electroscope anew, and observe the time t' required for the leaf to move over the specified distance. The reciprocal of this time interval may be taken as a measure of the total current (leakage current plus current carried by the ionized air between the plates).

(*c*) Place upon the plate *A* a tray containing *W* grams of the powdered mineral to be tested spread out in a thin layer, charge the electroscope again, and observe the time t'' required for the gold leaf to move over the specified distance. The reciprocal of this time interval may be taken as a measure of the total current (leakage current plus current carried by the ionized air between the plates).

Computations and results. — The current carried by the ionized air when the standard sample of uranium oxide is in place is measured by $(1/t' - 1/t)$, the current carried by the ionized air when the sample of mineral is in place is measured by $1/t'' - 1/t$, and the radio-activity of the mineral expressed in terms of the radio-activity of the standard sample of uranium oxide is found by dividing the second current by the first.

EXPERIMENT 108.

Study of a Radio-Active Transformation.

The object of this experiment is to familiarize the student with the method of studying those remarkable changes which take place in a radio-active substance.

Apparatus and work to be done. — Place about 50 grams of thorium hydroxide in the bottom of a small metal box, and suspend a small metal plate from the wooden or hard-rubber cover of the box. Connect the metal plate to the negative terminal and the metal box to the positive terminal of 110-volt direct-current mains, and allow the arrangement to stand about ten minutes. The sides of the metal box should be lined with thick paper to avoid the possibility of short circuiting the mains by touching the suspended plate to the sides of the vessel. Remove the plate, disconnect it from the mains, put it in place of the tray *MM* in the apparatus shown in Fig. 146, and determine repeatedly the time required for the leaf *L* to move over the chosen distance, noting the clock reading at the beginning and end of each determination.

Results. — Plot a curve of which the abscissas represent elapsed times reckoned from the instant of removal of the small plate from the thorium hydroxide vessel, and of which the ordinates represent the radio-activity of the material which has been deposited upon the small plate.

The radio-activity of thorium is accompanied by the development of a gaseous emanation which is itself radio-active. The radio-activity of this emanation results in the production of a non-volatile material which at the instant of formation is positively charged. This material is carried toward the negatively charged metal plate which is hung in the thorium hydroxide vessel and forms a deposit thereon. According to Rutherford, this deposit, which is called "thorium *A*," is not radio-active, but it undergoes a change whereby it is converted into "thorium *B*," which

is radio-active, and the radio-activity of thorium B transforms it into another material of which the radio-activity is negligibly small in comparison with the radio-activity of thorium B. The transformation of thorium A into thorium B takes place according to the exponential law of decay (one half of a given amount of thorium A being converted into thorium B in one hour), and the transformation of thorium B also takes place according to an exponential law of decay (one half of a given amount of thorium B being transformed in eleven hours). The details of the analysis of the curve above determined is fully explained by Rutherford, *Radio-active Transformations*, pages 48 to 50.

APPENDIX.

The Reduction of Telescope and Scale Readings.

In reading angular deflections by means of telescope and scale the deflection Δ is understood to mean the difference between the zero or middle reading and the deflected reading, or half the difference between oppositely deflected readings. Let D be the distance of the scale from the mirror, expressed in scale divisions, then:

(*a*) For small deflections the ratio $\Delta/2D$ is approximately equal to the angle of deflection in radians and also approximately equal to the sine or the tangent of the angle.

(*b*) For greater deflections we may employ the following series in which ϕ is the angle of deflection:

$$\phi \text{ in degrees} = 28.648\frac{\Delta}{D}\left(1 - \tfrac{1}{3}\frac{\Delta^2}{D^2} + \tfrac{1}{5}\frac{\Delta^4}{D^4}\cdots\right)$$

$$\tan\phi = \frac{\Delta}{2D}\left(1 - \tfrac{1}{4}\frac{\Delta^2}{D^2} + \tfrac{1}{8}\frac{\Delta^4}{D^4}\cdots\right)$$

$$\sin\phi = \frac{\Delta}{2D}\left(1 - \tfrac{3}{8}\frac{\Delta^2}{D^2} + \tfrac{31}{128}\frac{\Delta^4}{D^4}\cdots\right)$$

$$\sin\tfrac{1}{2}\phi = \frac{\Delta}{4D}\left(1 - \tfrac{11}{32}\frac{\Delta^2}{D^2} + \tfrac{431}{2048}\frac{\Delta^4}{D^4}\cdots\right)$$

For deflections not exceeding 300 divisions on a scale distant 1,000 divisions from the mirror, the first corrective term of the series gives values that are correct to within one fourth of one per cent., which is sufficiently exact for most purposes. The following table gives the numbers which must be subtracted from the observed deflection Δ to give a corrected deflection Δ' which is proportional to the tangent of the angle of deflection; or $\tan\phi = k\Delta'$ where k is a constant.

D	Δ=50	=100	Δ=150	Δ=200	Δ=250	Δ=300	Δ=350	Δ=400	Δ=450	Δ=500
1000	0.03	0.25	0.83	1.95	3.77	6.40	10.00	14.6	20.3	27.2
1200	0.02	0.17	0.58	1.37	2.65	4.52	7.09	10.4	14.6	19.6

For a more extended table see Kohlrausch, Physical Measurements, page 446.

Example. — Two angles are measured by the telescope and scale and it is desired to find the ratio of their tangents. The distance of the scale from the mirror is 1000 scale divisions ($= D$) and the observed deflections are 150 and 250 respectively. Subtracting 0.83 from 150 and subtracting 3.77 from 250, we have 124.2/246.2 as the required ratio of the two tangents.

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